Measuring Ocean Surface Winds and Currents from Space

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Talk Outline

1. Science rationale
2. Measurement approach
3. Proof of concept airborne results
4. Spaceborne measurement concept

Decadal Survey Recommendations

The 2017 NRC Decadal Review, ***Thriving on Our Changing Planet A Decadal Strategy for Earth Observation from Space***, has identified "***Coincident high-accuracy currents and vector winds to assess air-sea momentum exchange and to infer upwelling, upper ocean mixing, and sea-ice drift***" as a targeted observable for a potential Earth System Explorer mission (competed).

- Doppler scatterometry identified as a measurement technique

TARGETED OBSERVABLE	SCIENCE/APPLICATIONS SUMMARY	CANDIDATE MEASUREMENT APPROACH	Designated	Explorer	Incubation
Greenhouse Gases	**CO_2 and methane fluxes and trends,** global and regional with quantification of point sources and identification of source types	Multispectral short wave IR and thermal IR sounders; or lidar**		X	
Ice Elevation	**Global ice characterization** including elevation change of land ice to assess sea level contributions and freeboard height of sea ice to assess sea ice/ocean/atmosphere interaction	Lidar**		X	
Ocean Surface Winds & Currents	**Coincident high-accuracy currents and vector winds** to assess air-sea momentum exchange and to infer upwelling, upper ocean mixing, and sea-ice drift.	Radar scatterometer		X	
Ozone & Trace Gases	**Vertical profiles of ozone and trace gases** (including water vapor, CO, NO_2, methane, and N_2O) globally and with high spatial resolution	UV/IR/microwave limb/nadir sounding and UV/IR solar/stellar occultation		X	
Snow Depth & Snow Water Equivalent	**Snow depth and snow water equivalent** including high spatial resolution in mountain areas	Radar (Ka/Ku band) altimeter; or lidar**		X	
Terrestrial Ecosystem Structure	**3D structure of terrestrial ecosystem** including forest canopy and above ground biomass and changes in above ground carbon stock from processes such as deforestation & forest degradation	Lidar**		X	

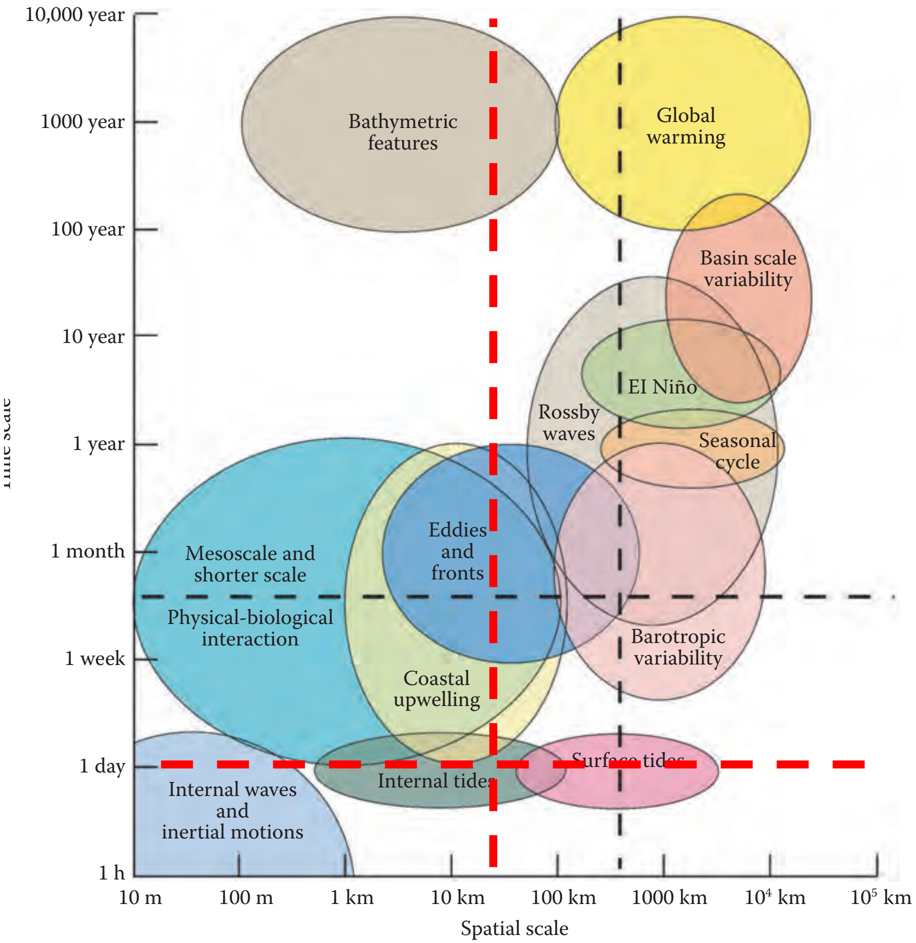
Why Winds and Surface Currents?

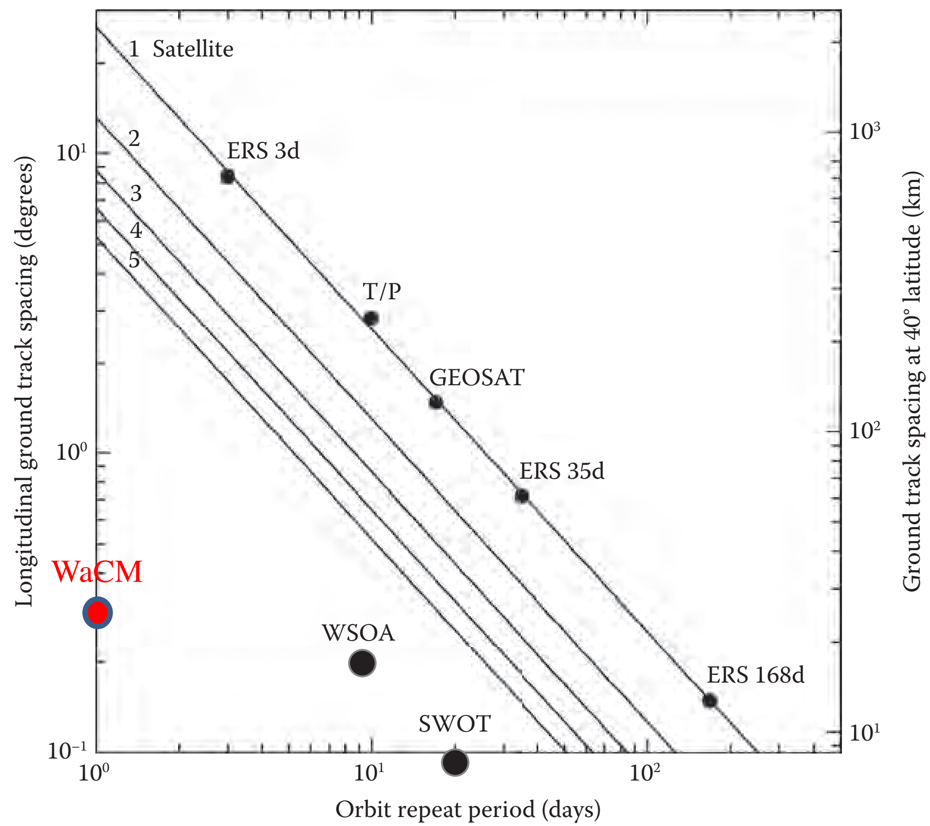
- Both are critical air-sea interaction variables that have a tight two-way coupling
  - Stress and stress derivatives drive both horizontal and vertical circulation
  - Currents provide a moving reference frame for stress and also modulate winds through heat transport/SST
- GCOS lists both surface vector winds and surface currents as Essential Climate Variables
- Surface currents and winds are also important for many civil applications
  - Coastal shipping
  - Marine debris dispersal
  - Disaster management due spills
  - Marine fisheries (upwelling of nutrients)
- Doppler scatterometry identified as a measurement technique
  - DopplerScatt (NASA IIP, AITT) is a proof of concept instrument to validate measurement physics, algorithms, technology readiness.

Current or Planned Observing Capabilities

- ***Ocean vector winds***
  - ***Community observing recommendation:***
    - Global coverage every 6 hours.
    - Coverage up to the coast
  - ***Actual capability:***
    - EUMETSAT ASCAT + ISRO SCATSAT-1 have global coverage ~once every 2 days, coastal coverage not possible within ~25 km of coast.
    - COWVR or future ISRO instrument may improve temporal coverage, but not coastal coverage. Coverage every 6 hours will require more satellites than currently planned.
- ***Surface Currents***
  - There is no capability planned for surface currents. SWOT will measure geostrophic (deep) currents, but surface currents are modified by winds. OSCAR product is based on very low resolution altimeter (geostrophic) currents and modeled wind contributions. It is not valid in coastal areas.

Ocean Sampling Requirements



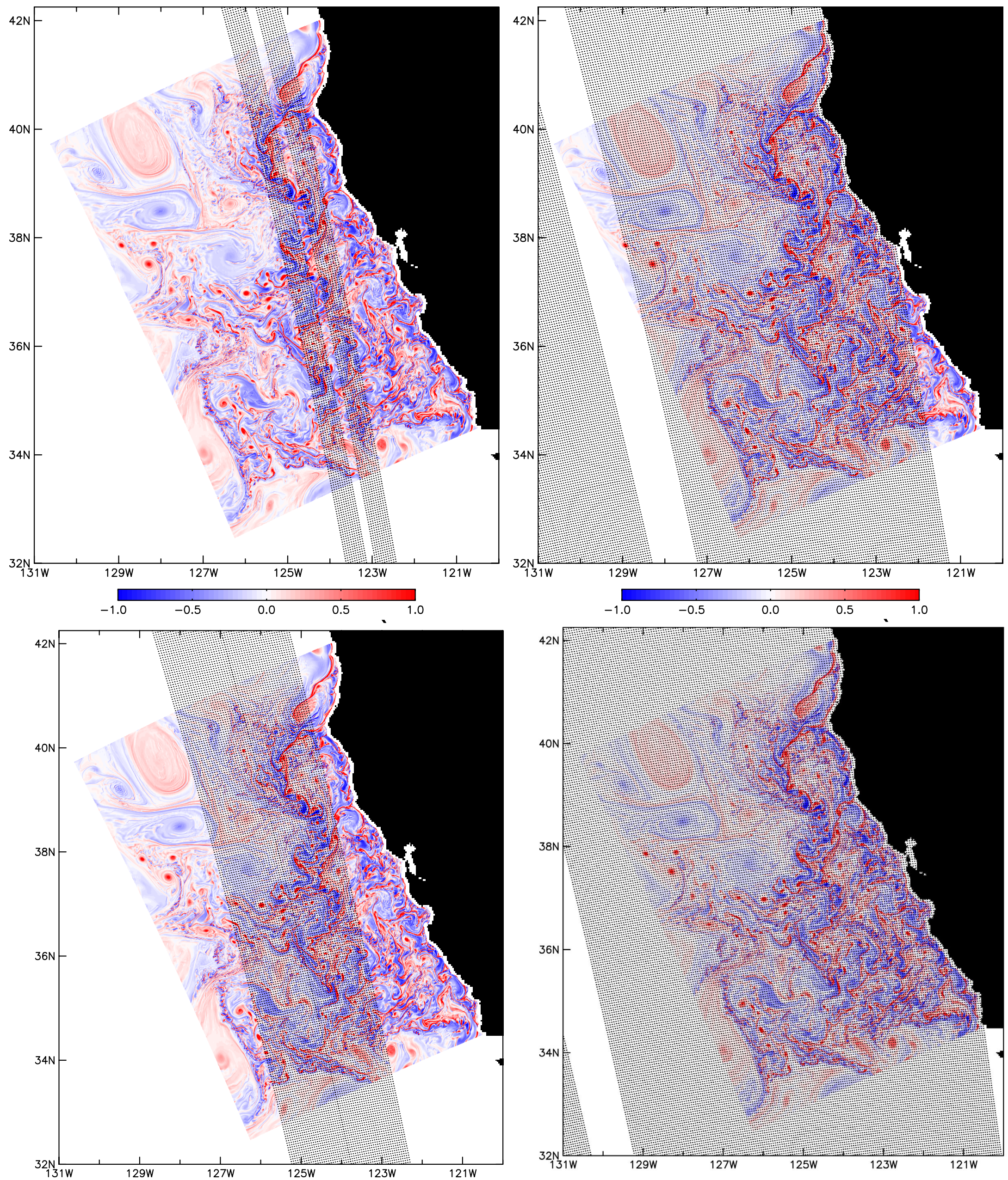


From Rodriguez et al, 2017,
In Satellite Altimetry over Ocean and Land Surfaces
Stammer & Cazenave, Eds

Orbital Sampling Characteristics

SWOT

WaCM
1300 km swath



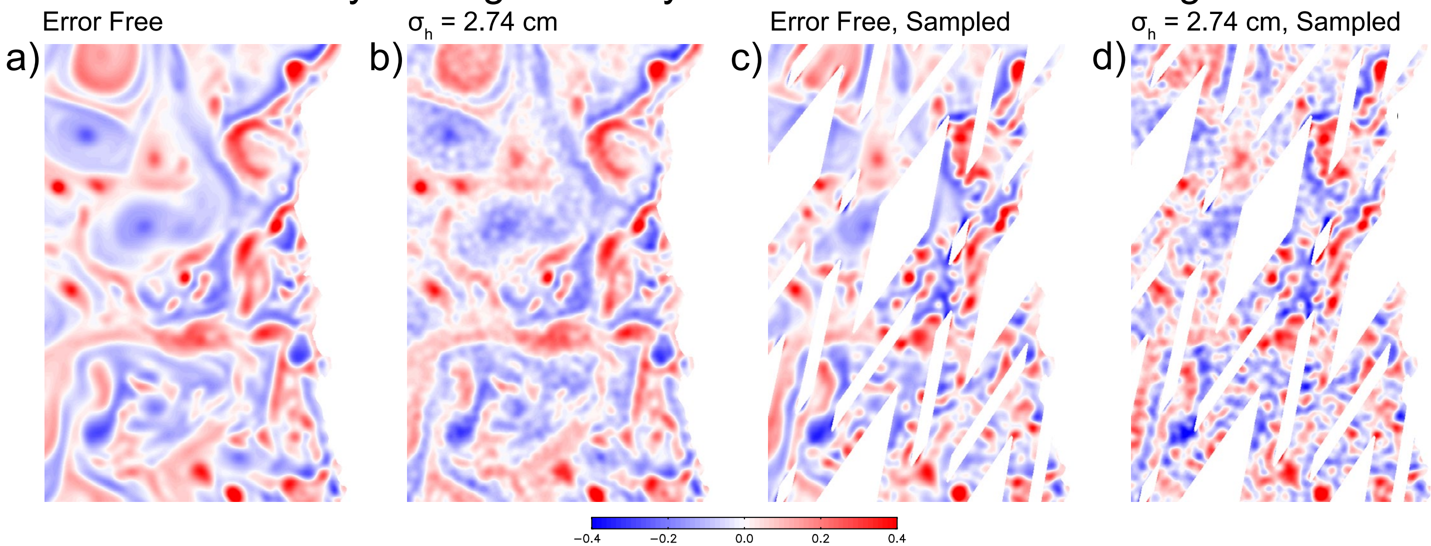
SKIM

WaCM
1800 km swath

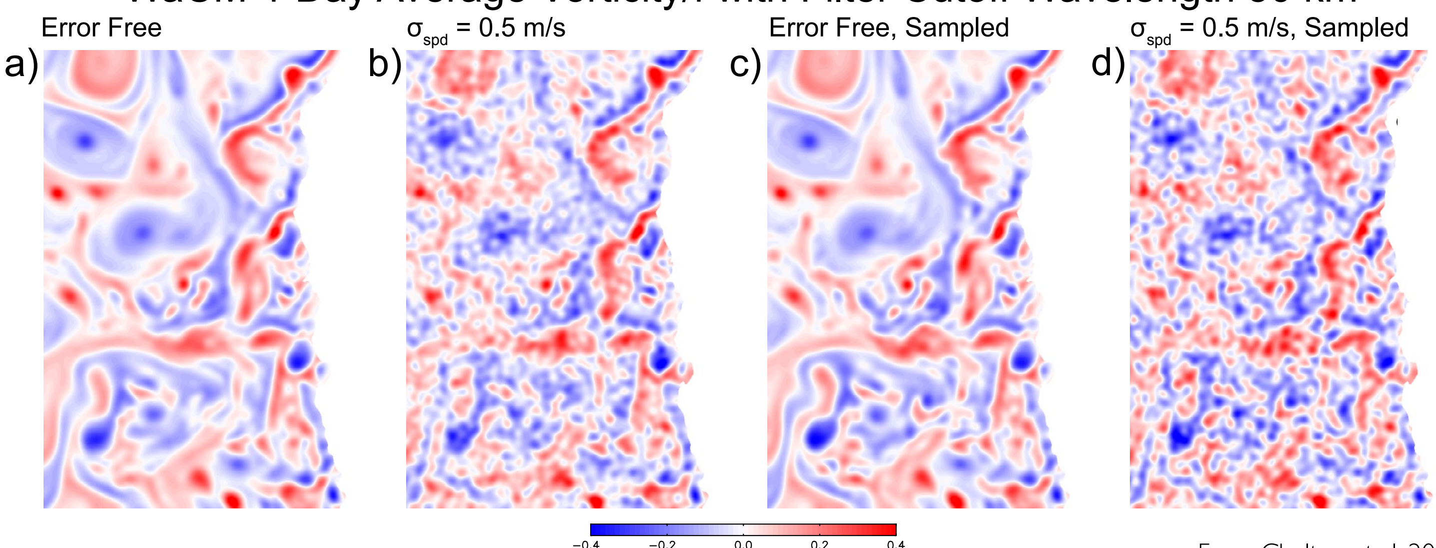
From Chelton et al, 2018
Prog. Ocean. In press

Wide swath & temporal sampling are key

SWOT 4-Day Average Vorticity/f with Filter Cutoff Wavelength 50 km

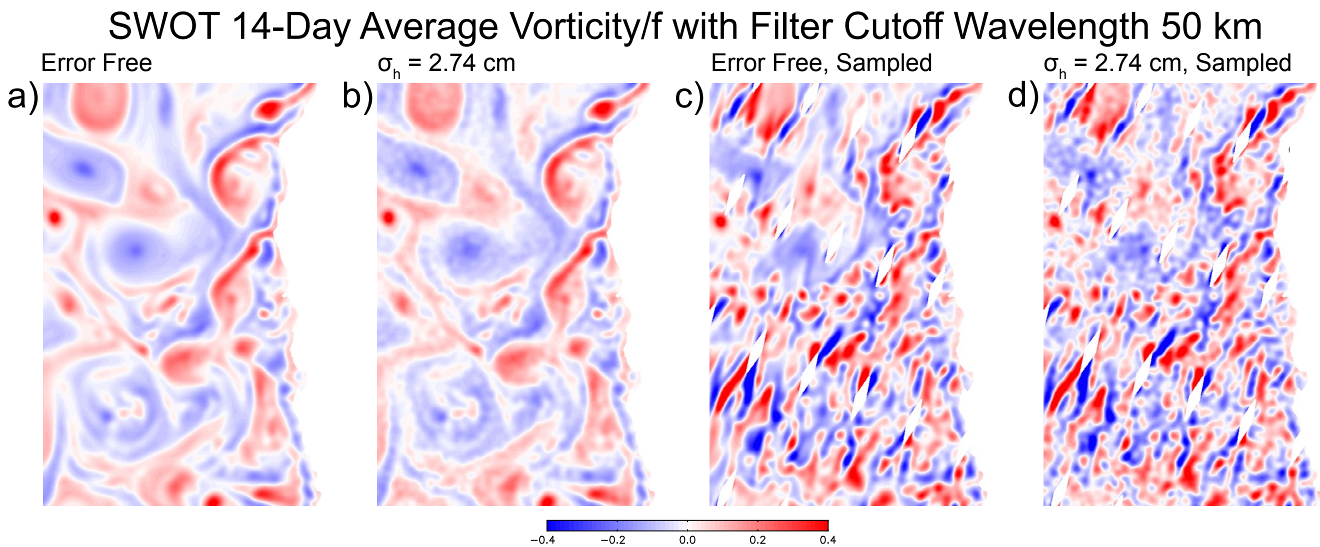


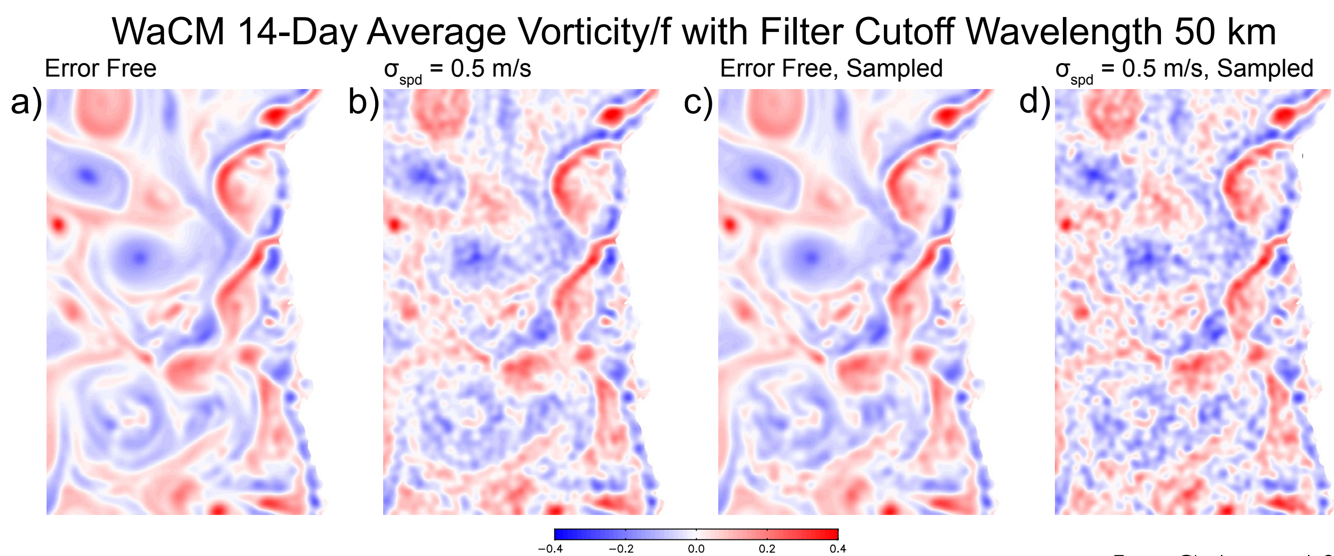
WaCM 4-Day Average Vorticity/f with Filter Cutoff Wavelength 50 km



From Chelton et al, 2018
Prog. Ocean. In press

Wide swath & temporal sampling are key



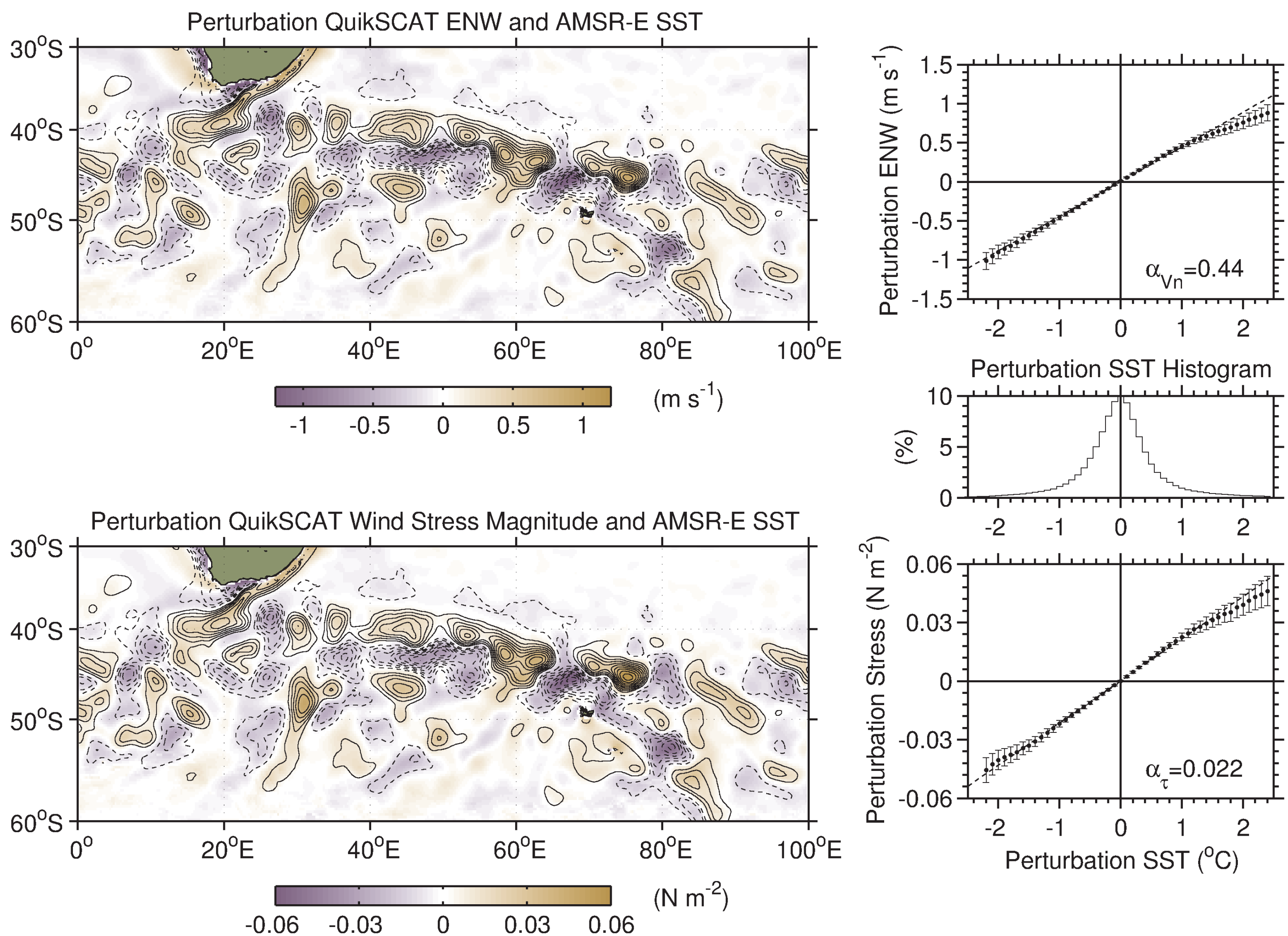


From Chelton et al, 2018
Prog. Ocean. In press

WaCM Science Priorities

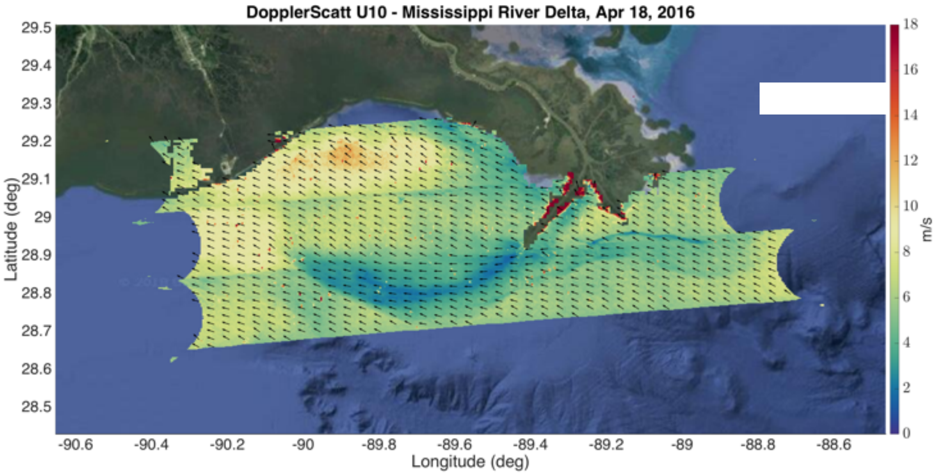
- WaCM science priorities are still evolving and we are engaging with the science and applications communities to refine the key topics and potential benefits for ancillary applications.
- Science areas:
  - Ocean-Atmosphere-Biosphere Interaction
  - Ocean-Atmosphere-Cryosphere Interaction
  - Equatorial Ocean-Atmosphere Interaction
  - Wind work

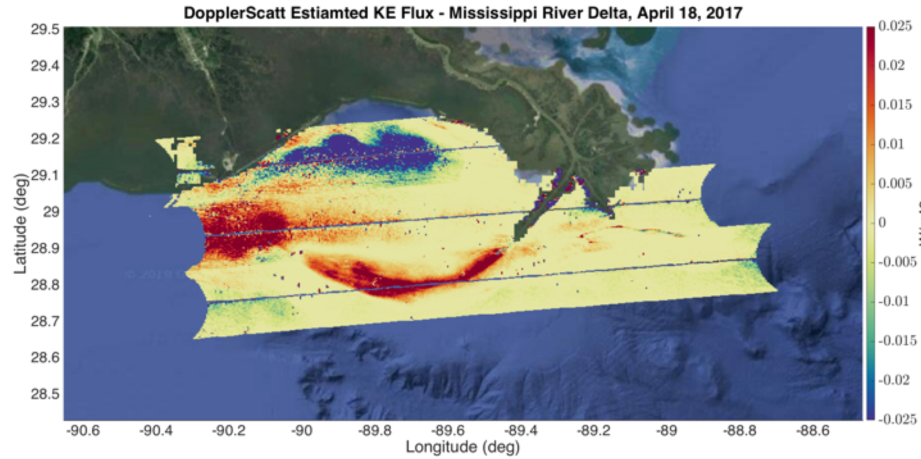
Modulation of Wind Stress by SST

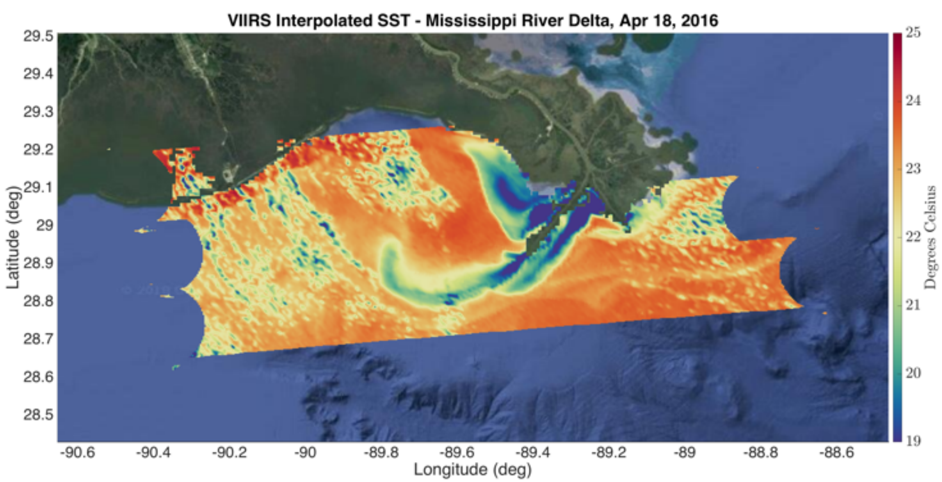


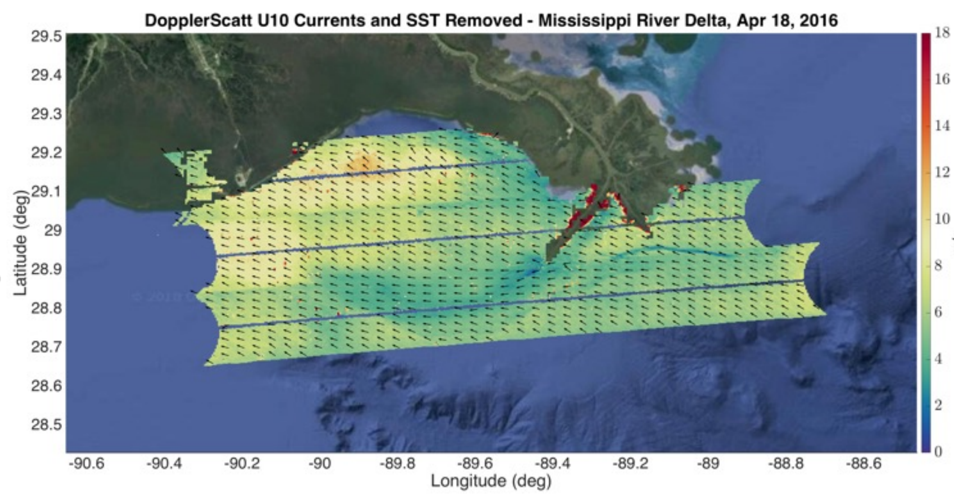
From O'Neill et al, 2012
J. Climate

Air Sea Interaction Examples: Current/SST Stress Modulation, KE Flux









Courtesy A. Wineteer, JPL

Ocean Productivity & Ekman Pumping

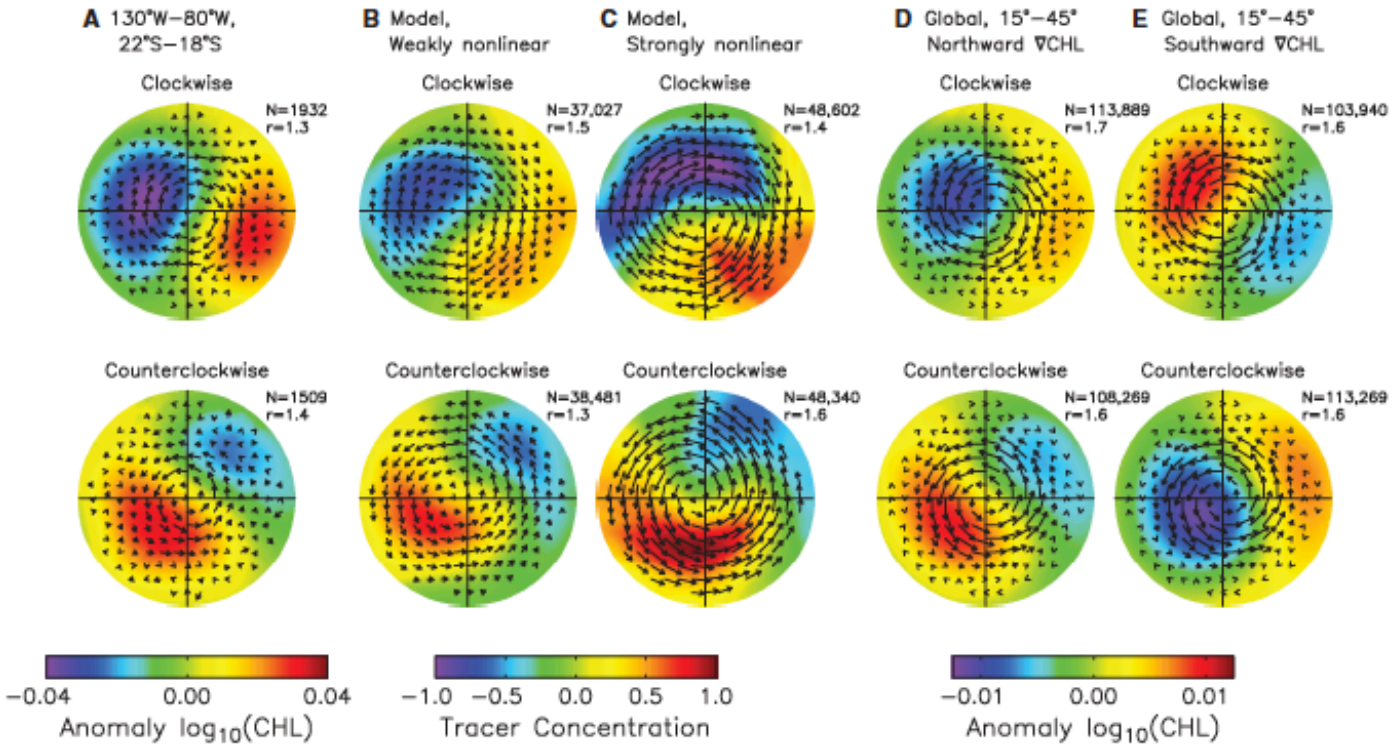


Fig. 3. Composite averages of filtered fields in a rotated and normalized coordinate system (22) within the interiors of CW (top panels) and CCW rotating eddies (bottom panels). **(A)** $\log_{10}$(CHL) in the region 18°S to 22°S, 130°W to 80°W. **(B)** A tracer field in a model simulation seeded with weakly nonlinear Gaussian eddies. **(C)** A tracer field in the model seeded with strongly nonlinear Gaussian eddies; **(D)** $\log_{10}$(CHL) globally between 15° and 45° latitude in regions of northward CHL gradient. **(E)** $\log_{10}$(CHL) globally between 15° and 45° latitude in regions of southward CHL gradient. The outer perimeter of each circle corresponds to twice the eddy radius scale L_s (22). The vectors in each panel are the gradient of the composite average SSH, which is proportional to the geostrophic velocity. The number N of eddy realizations in the composite average and the magnitude r of the ratio of the primary pole in the leading (left) half of each composite to the secondary pole in the trailing (right) half are labeled on each panel. The estimated 95% confidence intervals along profiles connecting the dipole extrema in each of these composite averages are shown in fig. S4.

From Chelton et al, Science, 2011

Arctic Ocean Freshwater (FW) Budget

Oceanic freshwater (FW) storage (S_{ref}=34.8)

Liquid: 74,000±7400 km^3

Sea ice: 10,000 km^3

Total FW inflow (km^3/yr):

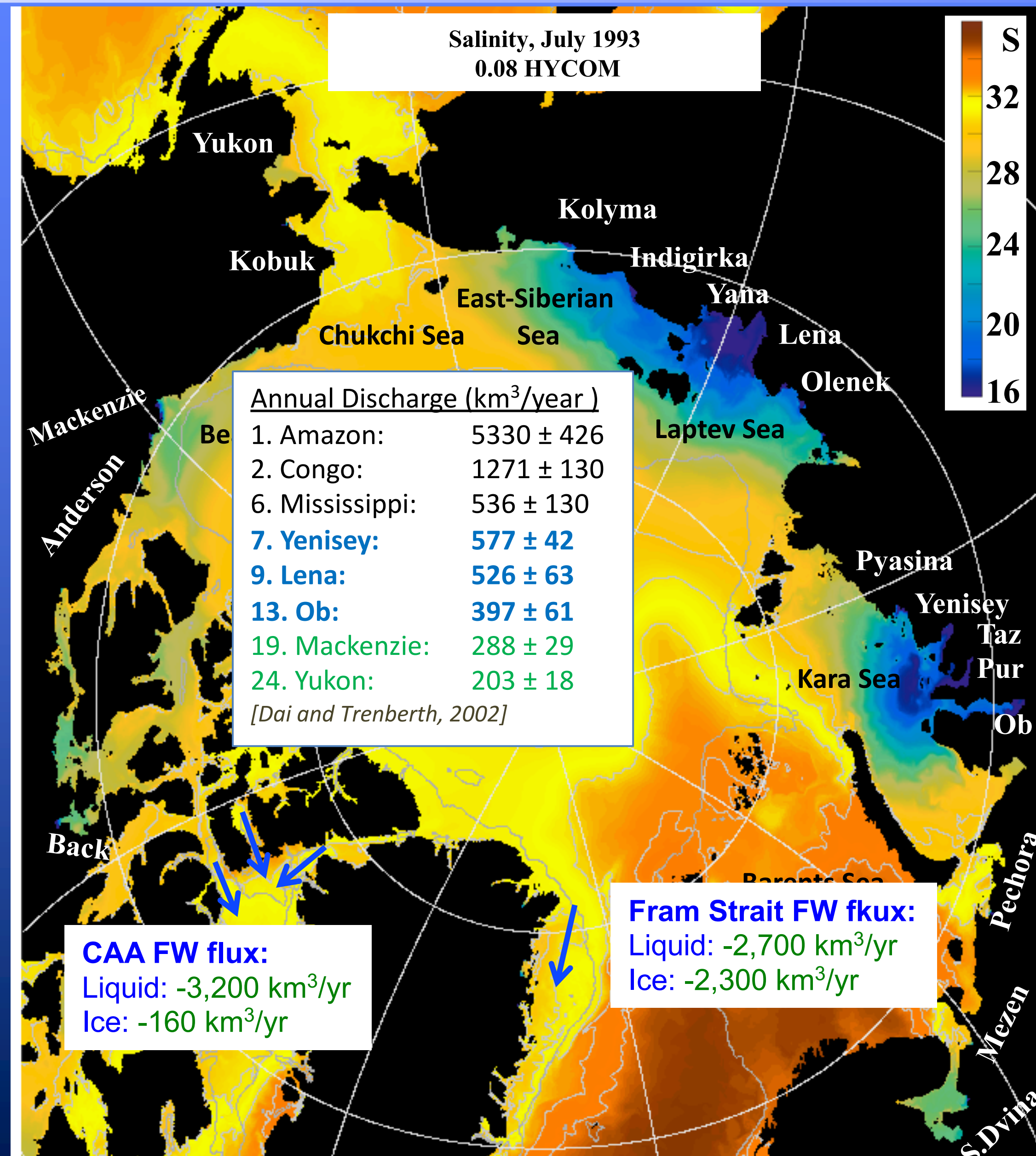
~7,950±400

Rivers:	3,200±110
P-E:	2,000±200
Bering Strait (liquid):	2,500±300
Bering Strait (ice):	140±40
Norwegian current:	250±50

Total FW outflow (km^3/yr):

~8,720±700

Based on: Serreze et al., 2006.



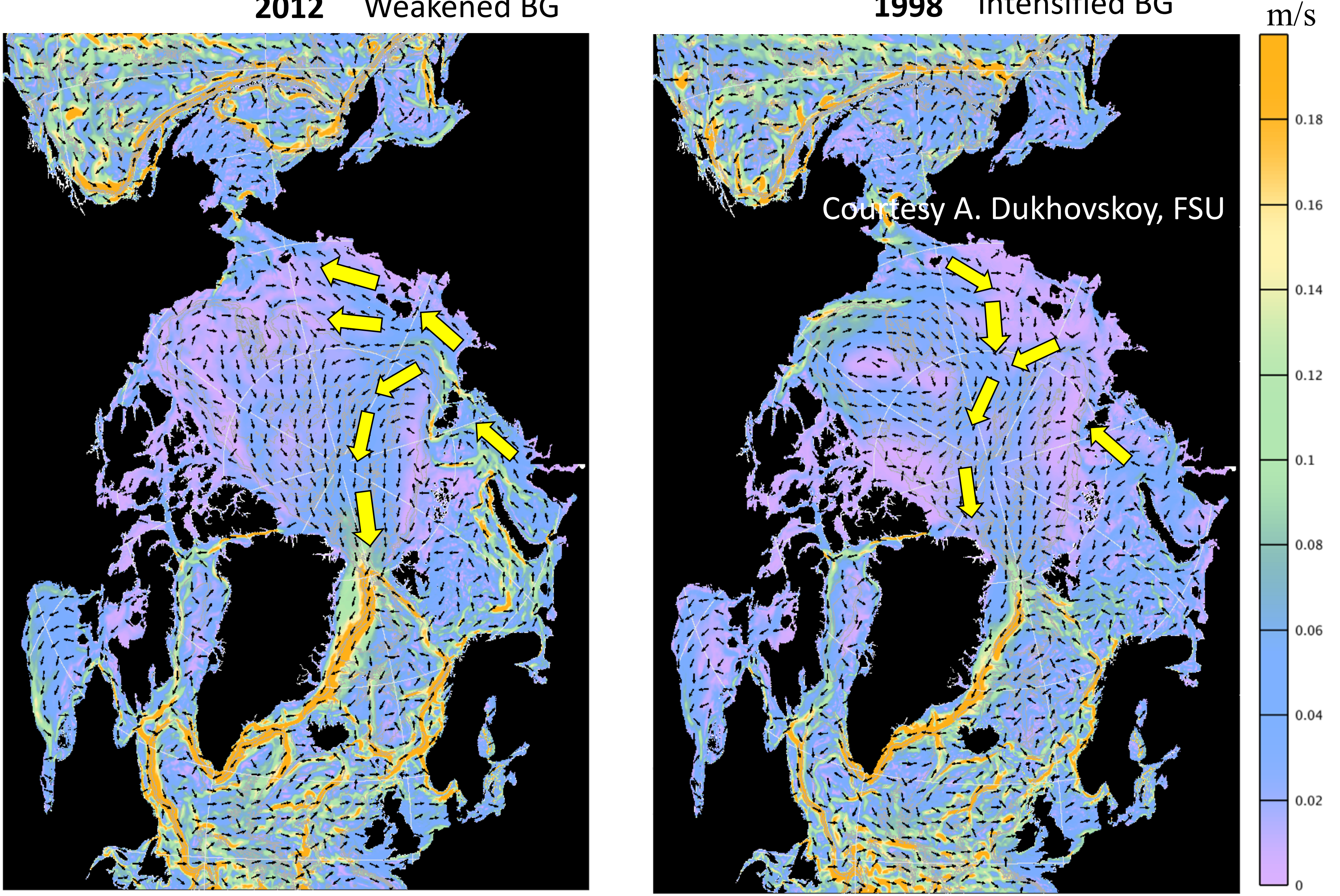
Annual Discharge (km^3/year)	
1. Amazon:	5330 ± 426
2. Congo:	1271 ± 130
6. Mississippi:	536 ± 130
7. Yenisey:	**577 ± 42**
9. Lena:	**526 ± 63**
13. Ob:	**397 ± 61**
19. Mackenzie:	288 ± 29
24. Yukon:	203 ± 18

[Dai and Trenberth, 2002]

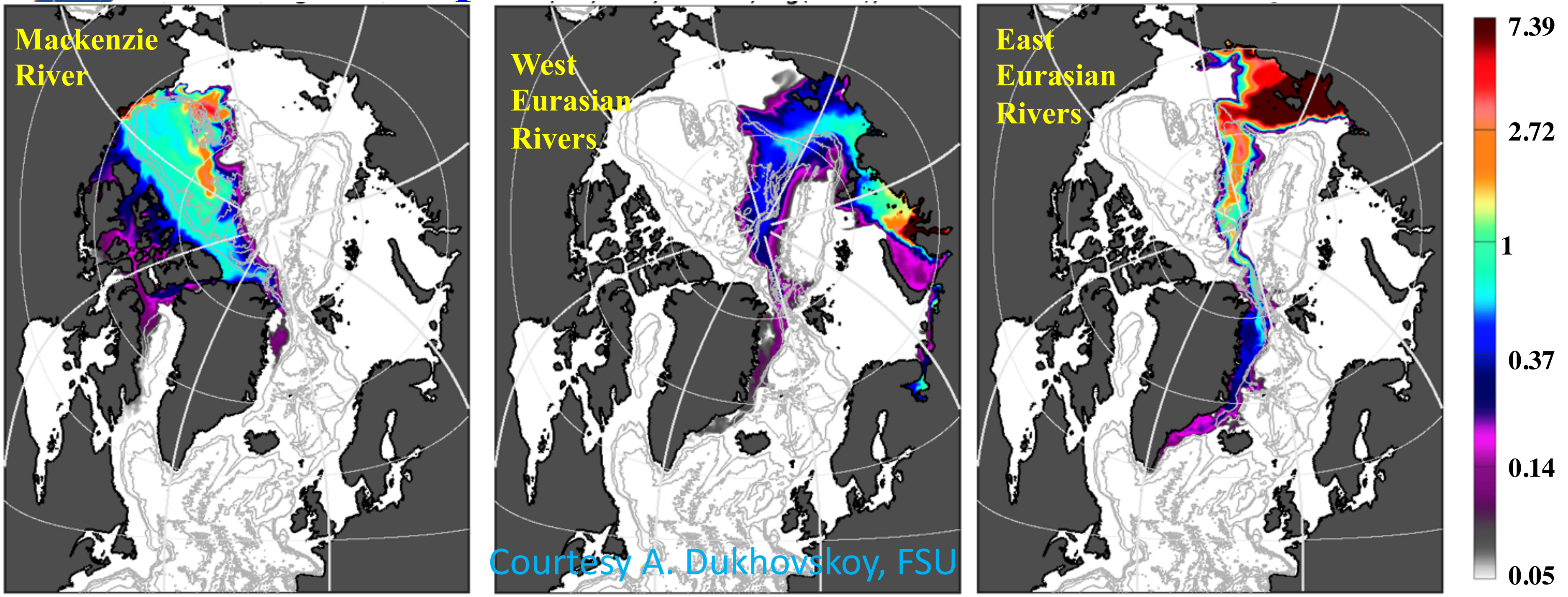
Different Ocean Circulation Patterns on the Arctic Shelf Under Different Wind Regimes (from a HYCOM-CICE Simulation)

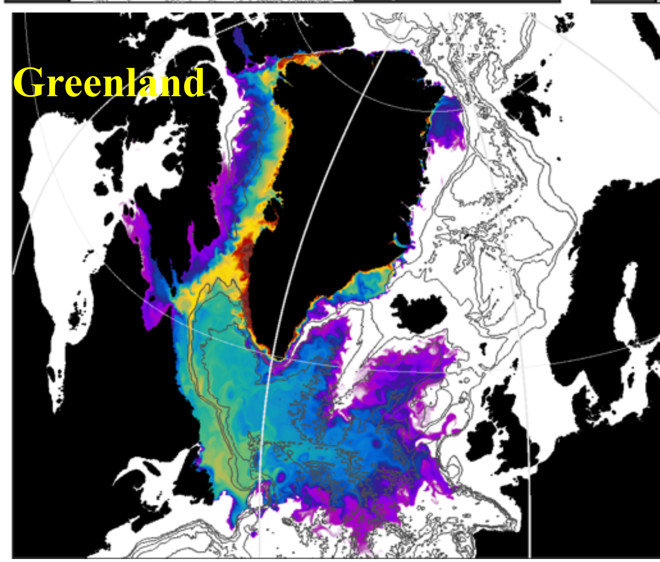
2012 Weakened BG

1998 Intensified BG



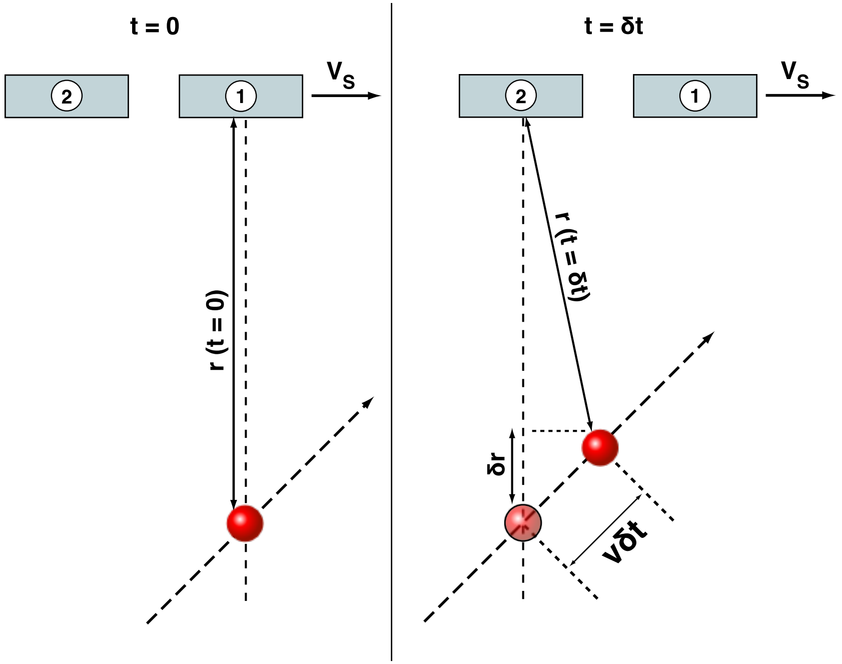
Pathways of River Runoff from the HYCOM-CICE Experiment with Passive Tracer

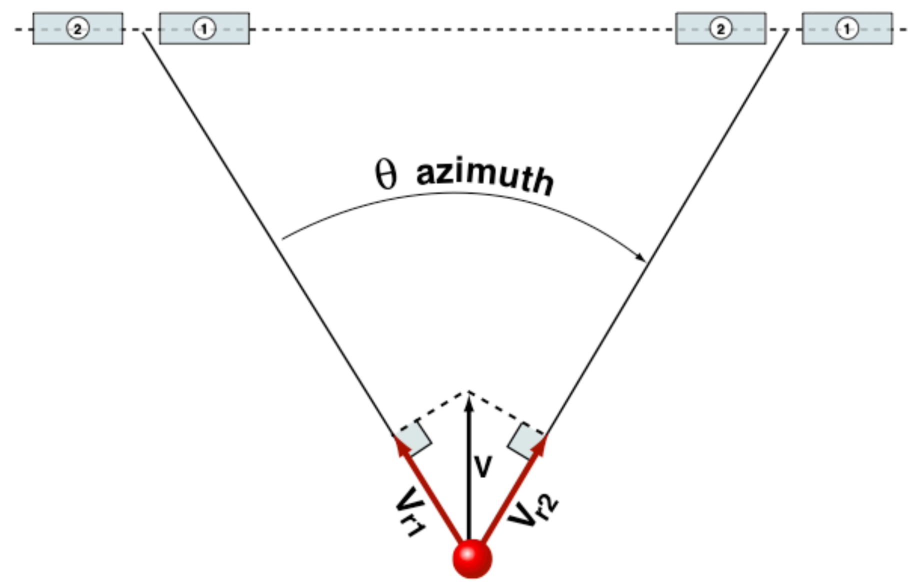




- Ocean model (HYCOM) simulations suggest that the concentration of freshwater from Canadian and Eurasian rivers is greatly diminished before moving into the North Atlantic Ocean.
  - Most fresh water entering the North Atlantic comes from Greenland.
- However, this is an open question that would benefit from better winds and surface currents.

Doppler Current Measurement Concept





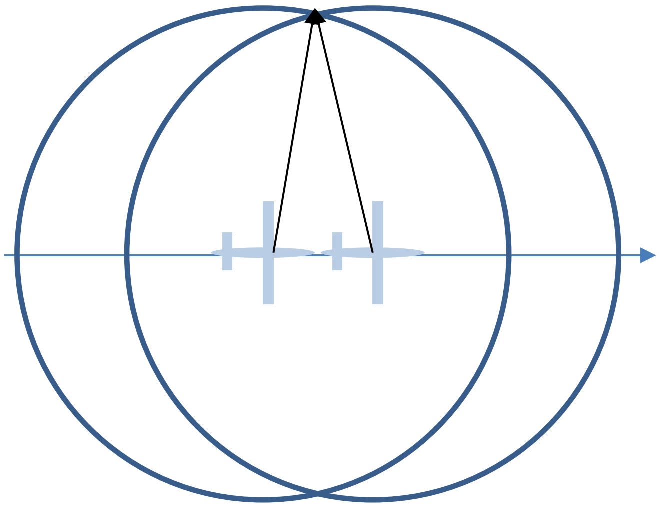
Doppler Phase Difference: $\Delta\Phi = 2k\Delta r = f_D\delta t$

Radial velocity component: $v_r = \Delta r/\delta t = \Delta\Phi/(2k\delta t)$

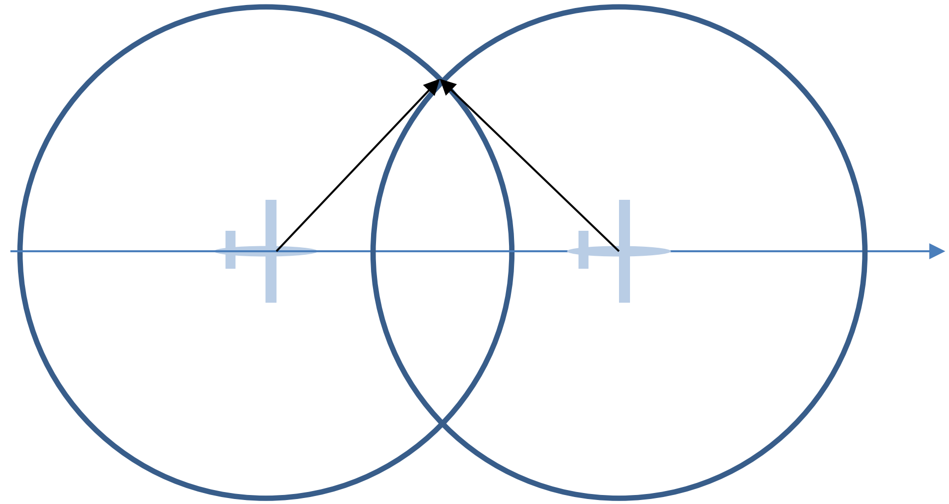
Vector currents are estimated by combining multiple (≧2) azimuth observations and projecting vector to the ocean surface.

- Radars provide coherent measurements: both the phase and the amplitude of a scattered signal are measured.
- The phase is proportional to the 2-way travel time (or range)
- The amplitude is proportional to the scattering strength of the traget
- Doppler measurements, f_D, are obtained by measuring the phase difference between pulses, $\Delta\Phi$. Noise is reduced by combining multiple pulses.

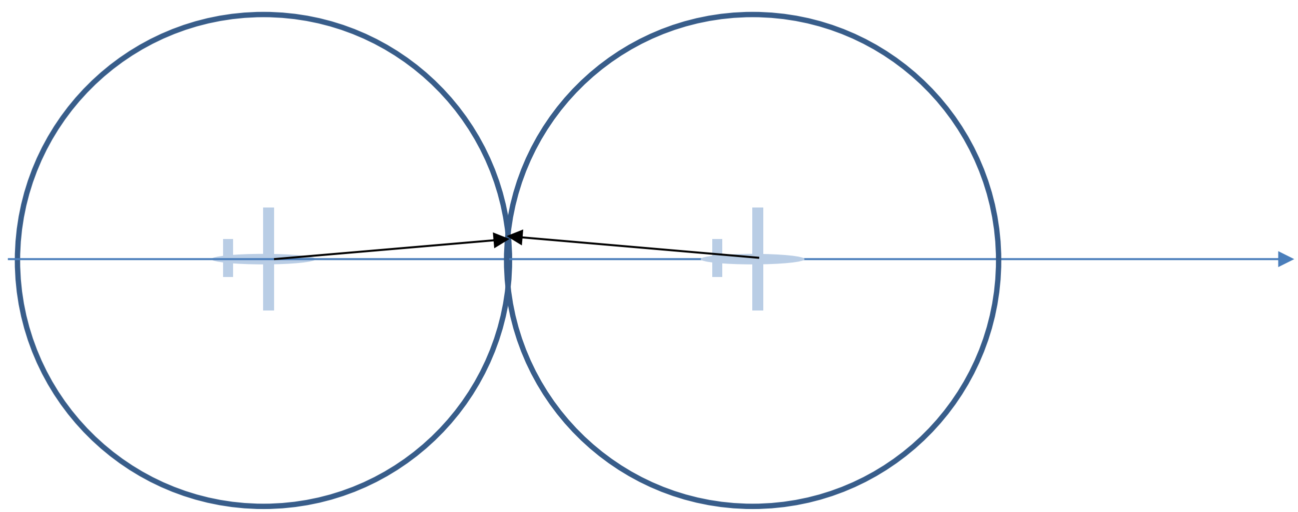
DopplerScatt Vector Estimation



Bad azimuth diversity



Good azimuth diversity



Bad azimuth diversity

DopplerScatt Overview

DopplerScatt Programmtic Overview

Scanning Doppler radar developed under NASA's IIP program
Becoming operational under NASA AITT program by 2019

Data Products:

1.Vector ocean surface currents
2.Vector ocean surface winds
3.Radar brightness maps (sensitive to surfactants such as oil films)
4. Surface wave 2D spectra (experimental)

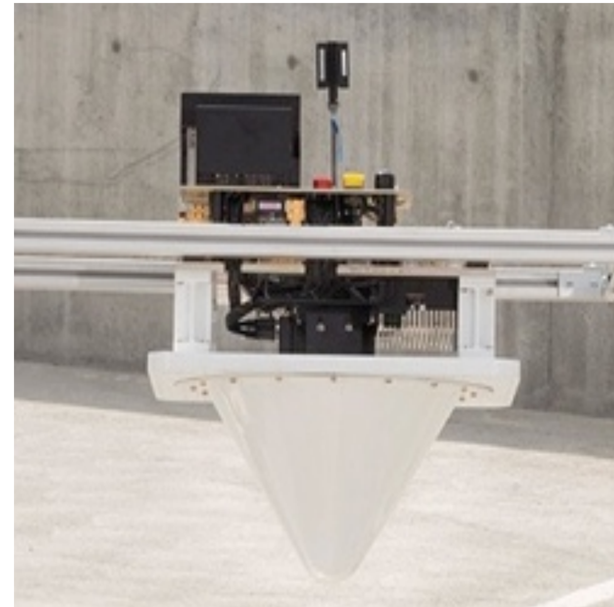
Data products are still being refined under AITT. Will be posted in NASA PODAAC when finished.

Mapping capabilities:

- 25 km swath
- maps 200km x 100km area in about 4 hrs
- 200m data product posting
- Mapping within ~600 m of coast
- ~5-10 cm/s radial velocity precision.
- ~ 1 m/s wind speed, <20° wind direction.

Campaigns flown/planned:

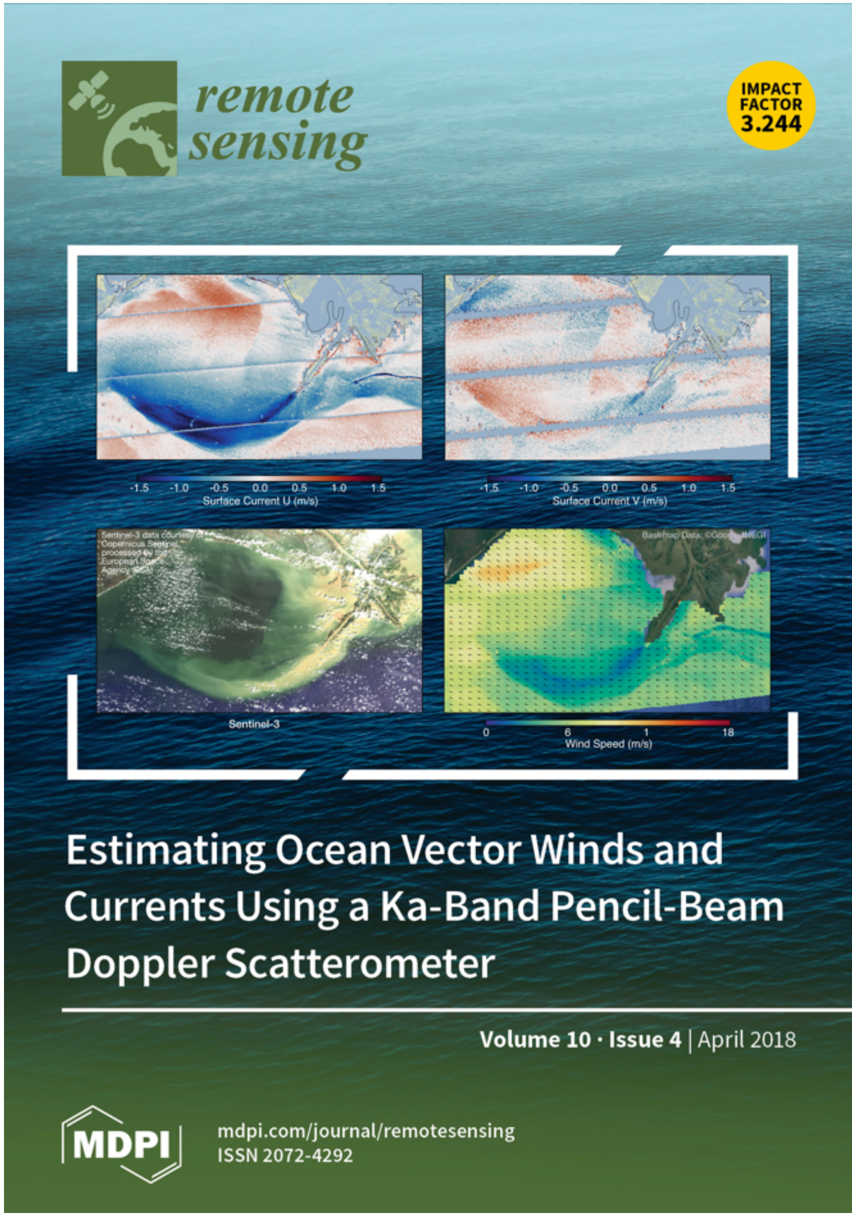
- Oregon coast (2016)
- SPLASH (Submesoscale Processes and Lagrangian Analysis on the Shelf) in Mississippi River Plume
- (CARTHE) & Taylor Oil Platform Plume (NOAA), April 18-28, 2017.
- KISS-CANON in Monterey Bay May 1-4, 2017.
- Gulf of Mexico Eddy/Chevron (March, 2018)
- California current (August, 2018)



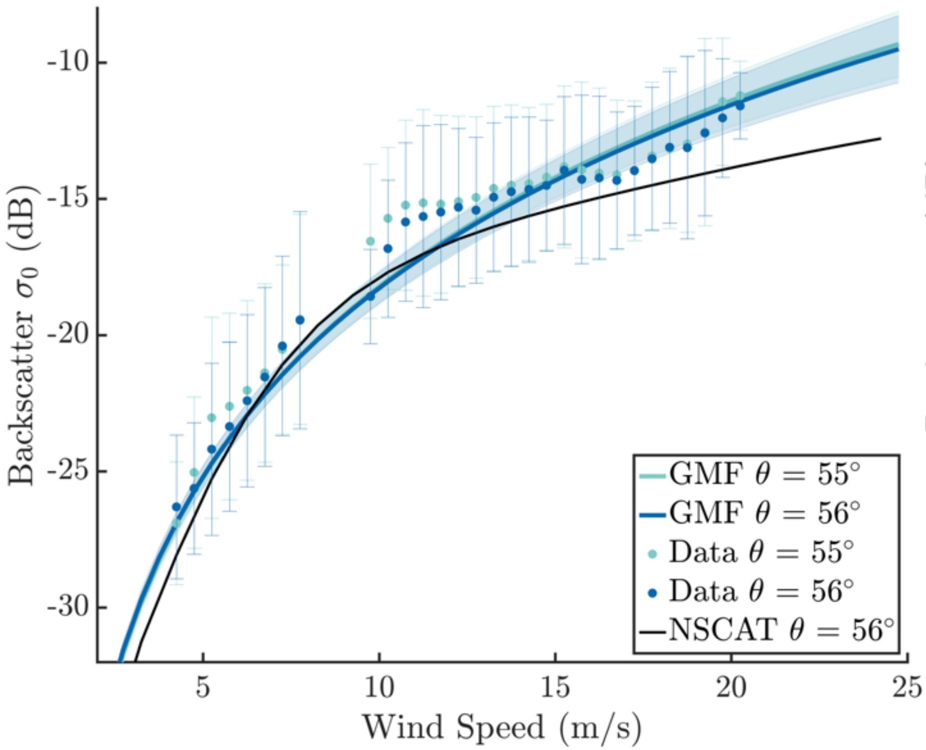
DopplerScatt instrument. It has been deployed on a DOE King Air and will transition to an operational instrument in the NASA King Air B200.

Measurement Feasibility

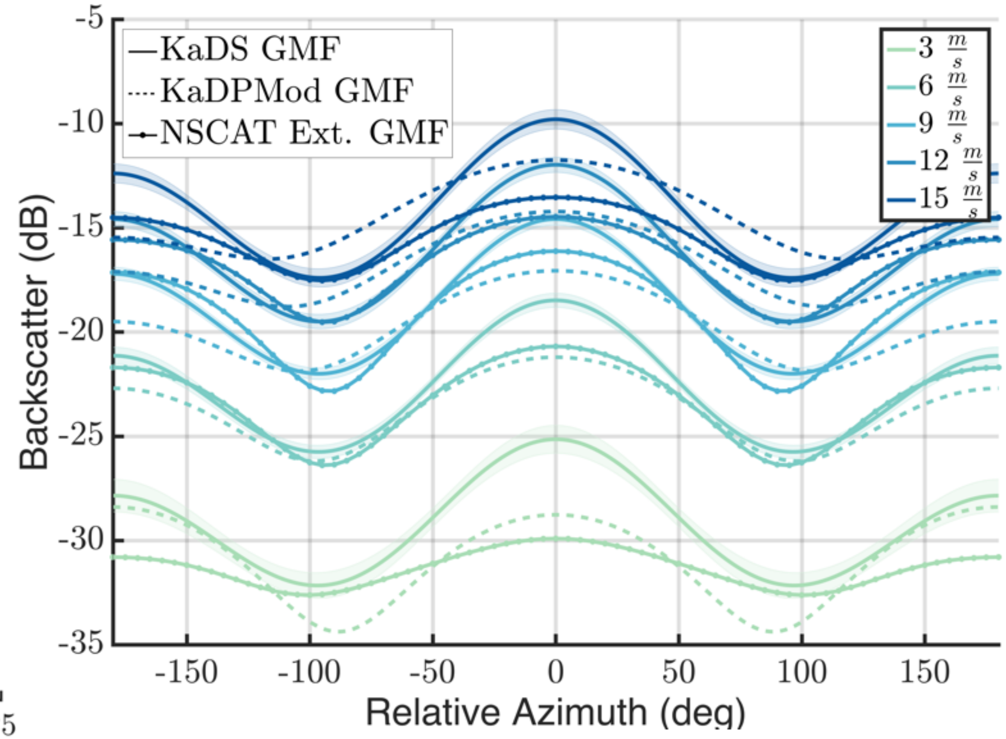
- Key questions:
  - How sensitive is Ka-band to wind speed and direction?
  - What surface velocity is DopplerScatt measuring?
  - Do we understand measurement errors and how do they scale to measurements from space?



Scatterometer Wind Estimation



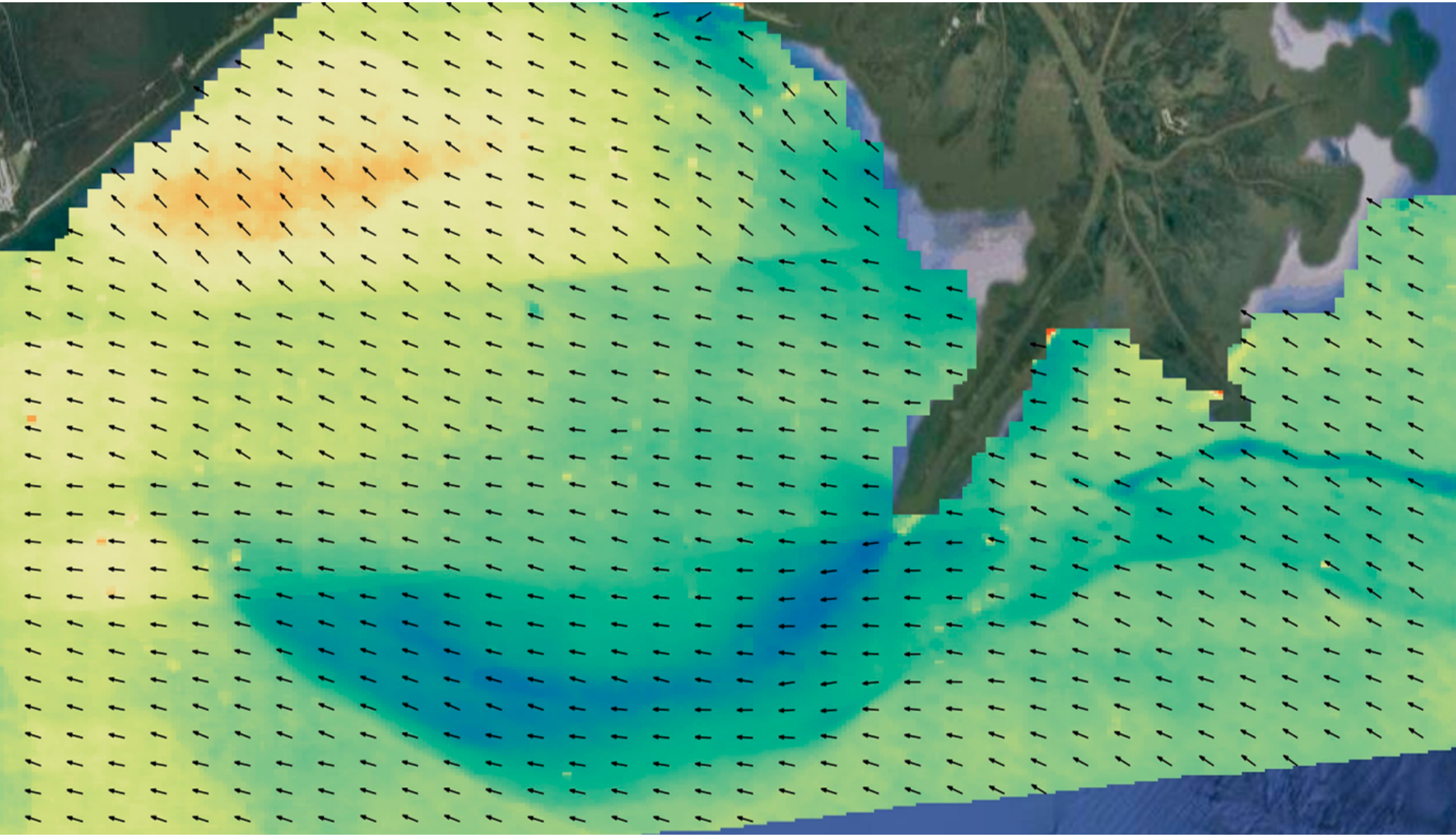
The mean radar backscatter increases with wind speed.



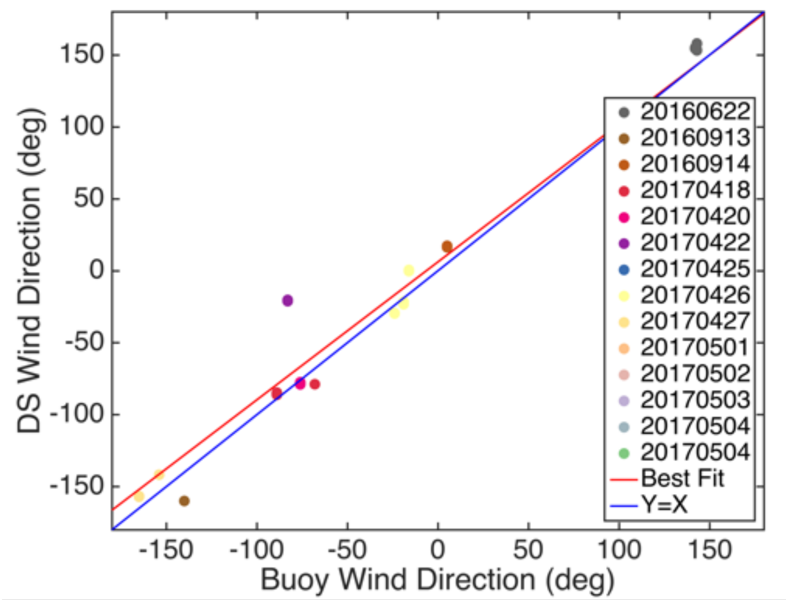
The backscatter intensity is modulated as a function of azimuth angle relative to wind direction.

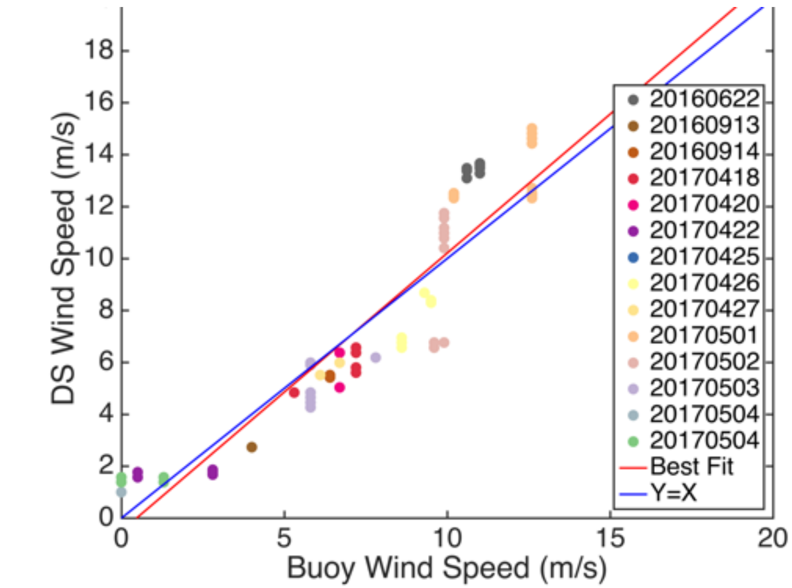
- By combining measurements from multiple azimuth angles, wind speed and direction can be estimated. Ku & Ka backscatter have similar characteristics, so both are suitable for wind estimation.
- Experiments have shown that backscatter is proportional to wind stress (although normally parametrized as neutral wind).

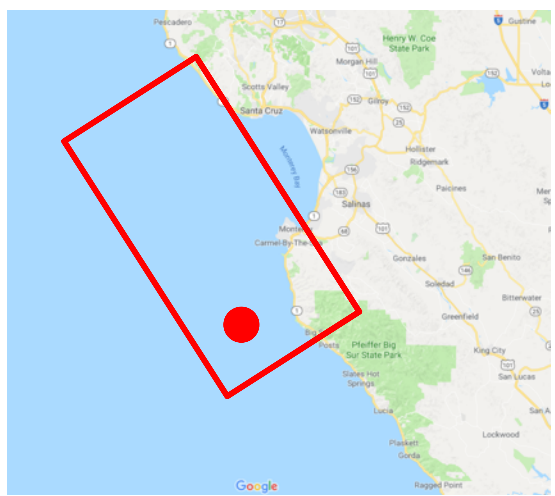
DopplerScatt Winds

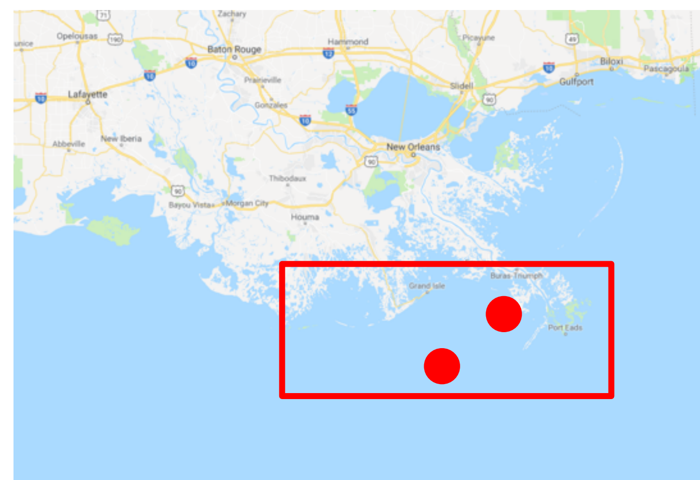


DopplerScatt Wind Validation

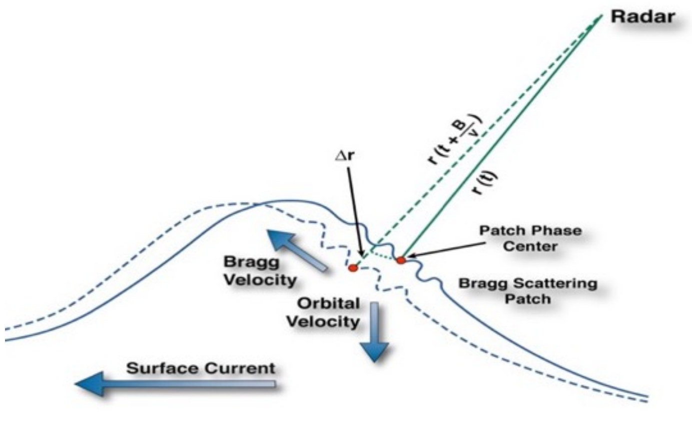


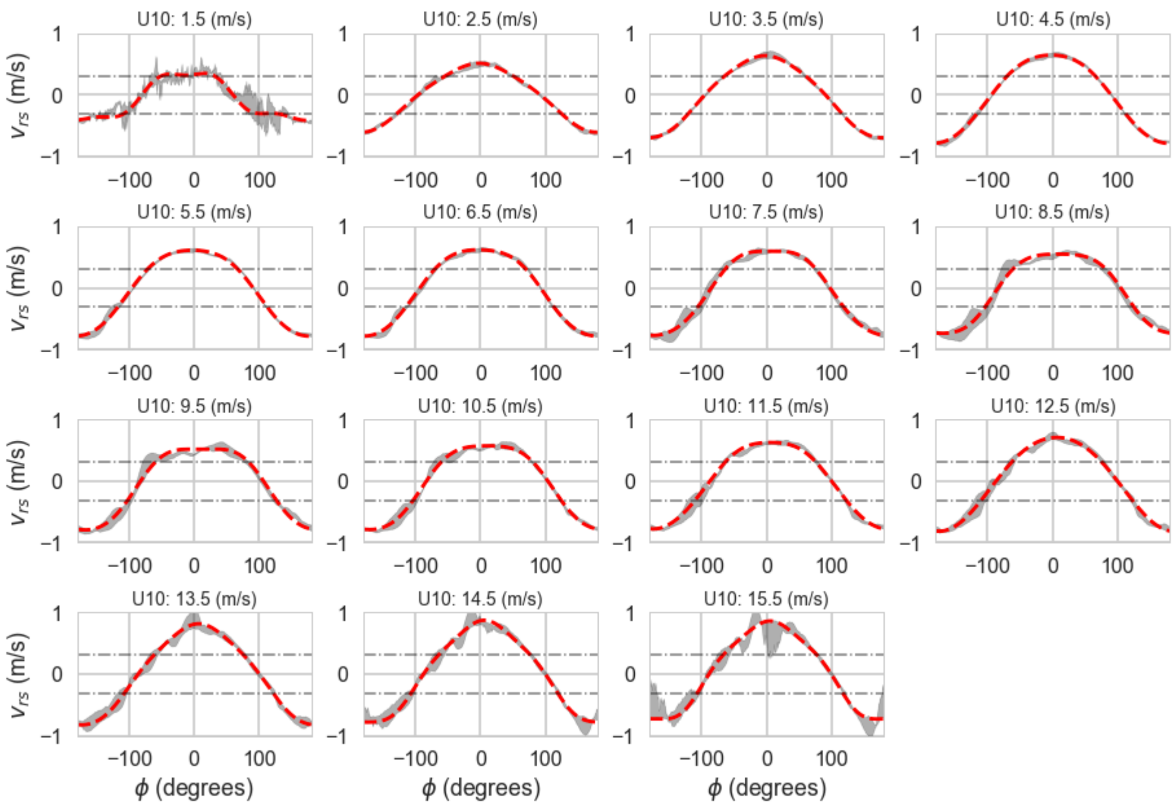






Wind/Wave Contamination





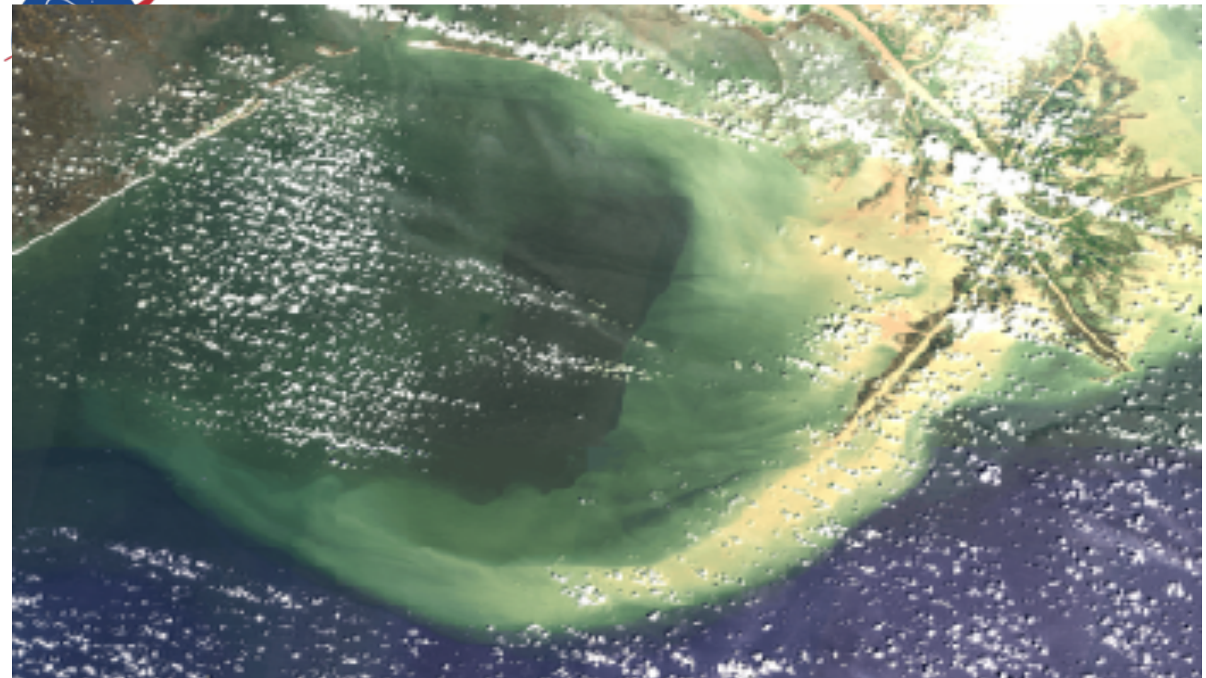
DoppelScatt measures the velocity of capillary (1.5 cm wavelength) waves modulated by gravity wave radial velocity.

Differential brightness between peaks and troughs introduces a bias similar to the EM bias in altimetry.

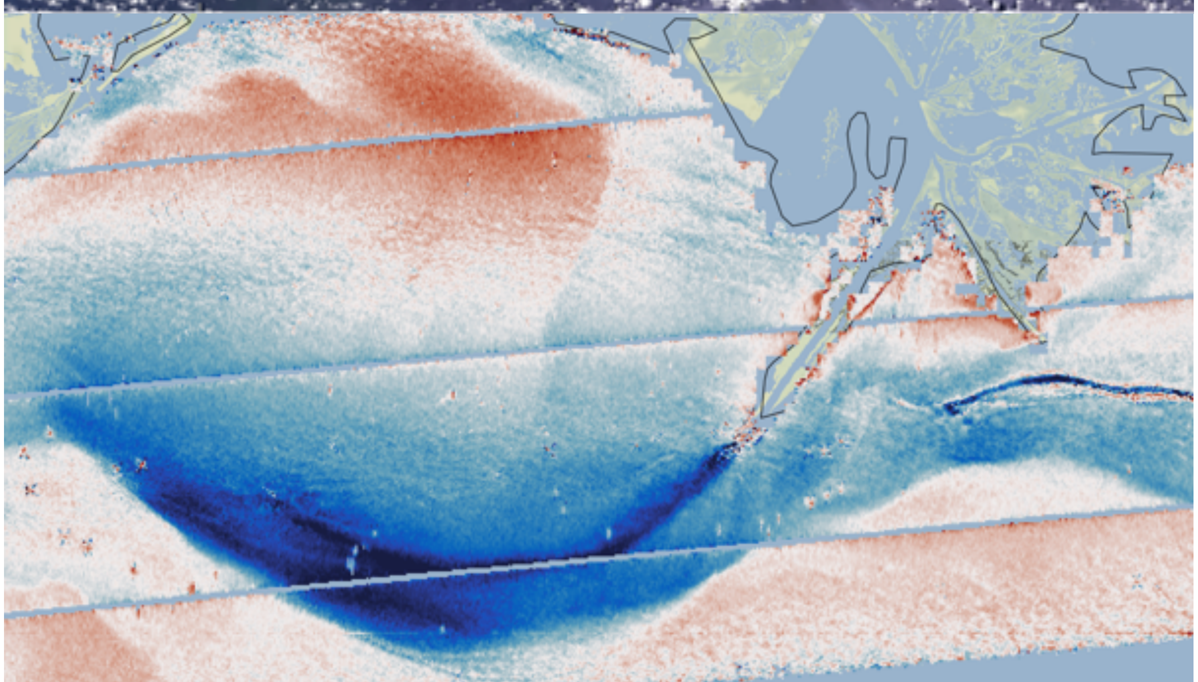
At this time, wind/wave biases are removed via an empirical function.

Unfortunately, this also removes some desirable components (e.g. Stokes drift)

The next set of DopplerScatt experiments (August 2018) will concentrate on improving this current correction.



Sentinel 3 2017-04-18
Courtesy of Copernicus Sentinel, processed by ESA



DopplerScatt surface current U component.

Circulation pattern matches Sentinel 3 color pattern very closely.

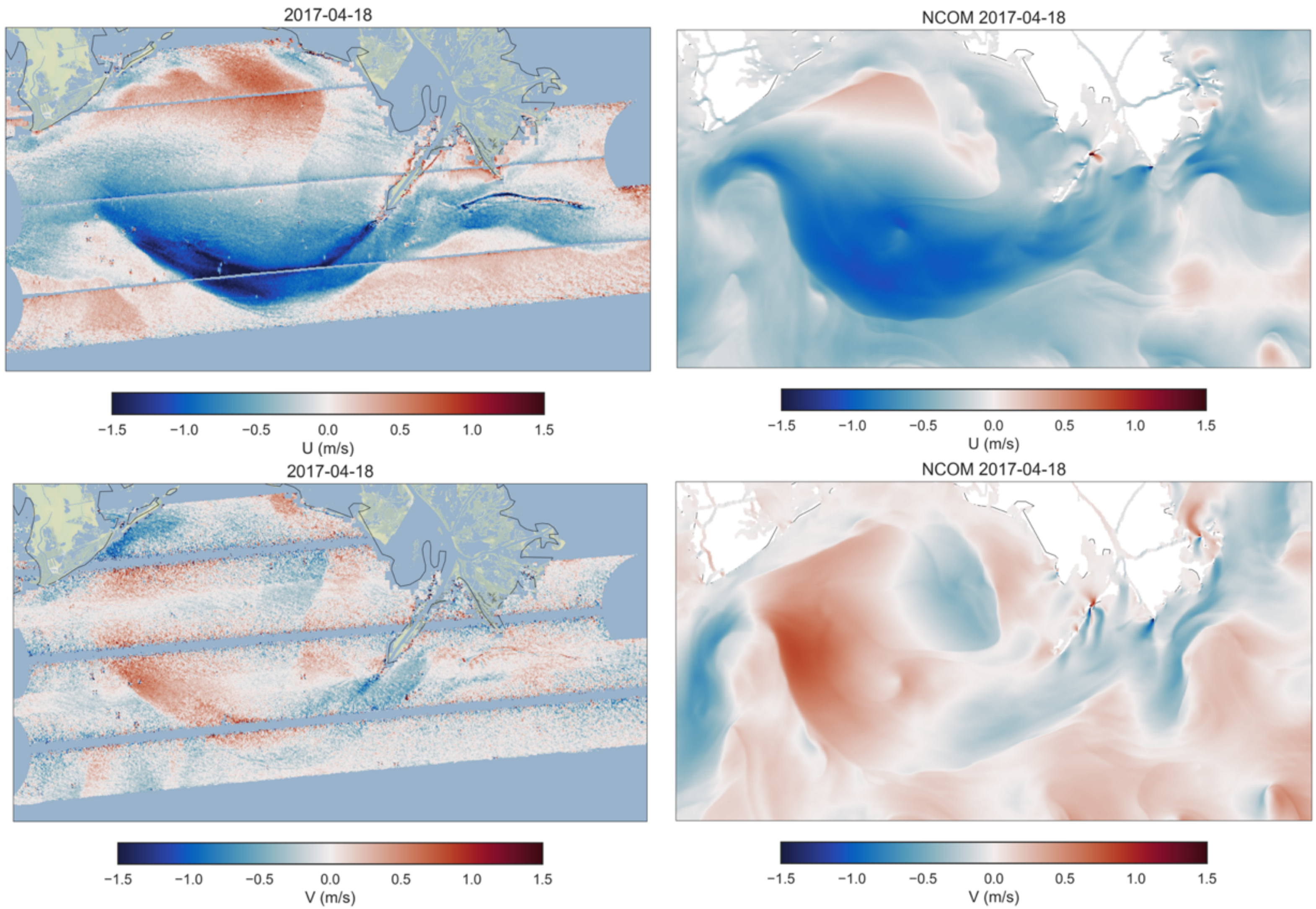
SPLASH 2017-04-18

NCOM Data courtesy G. Jacobs & NRL NCOM Team

DopplerScatt | NCOM

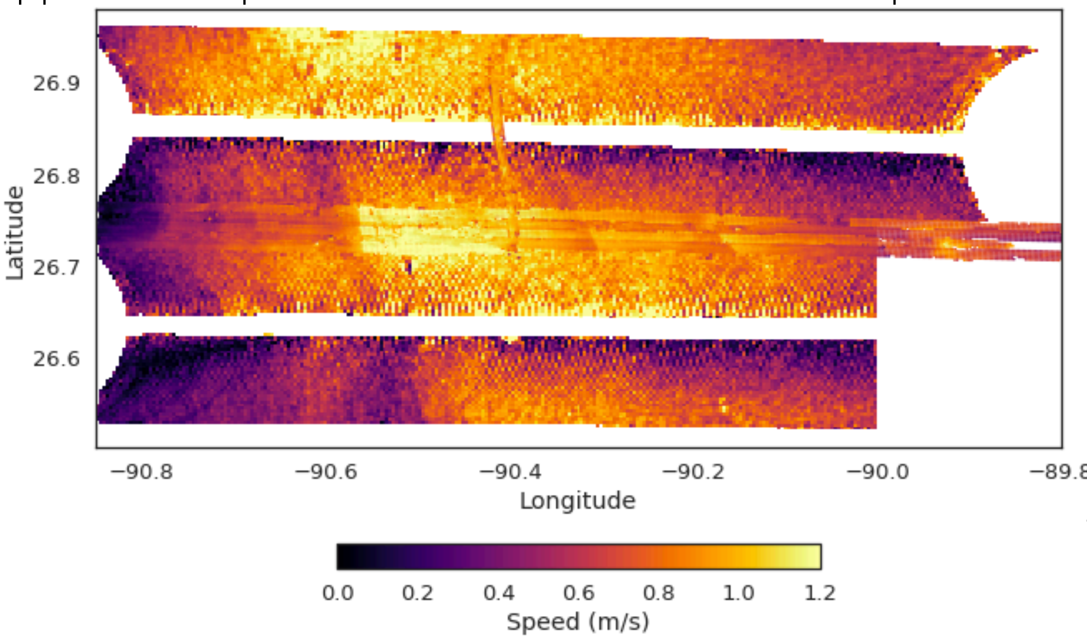
U

V



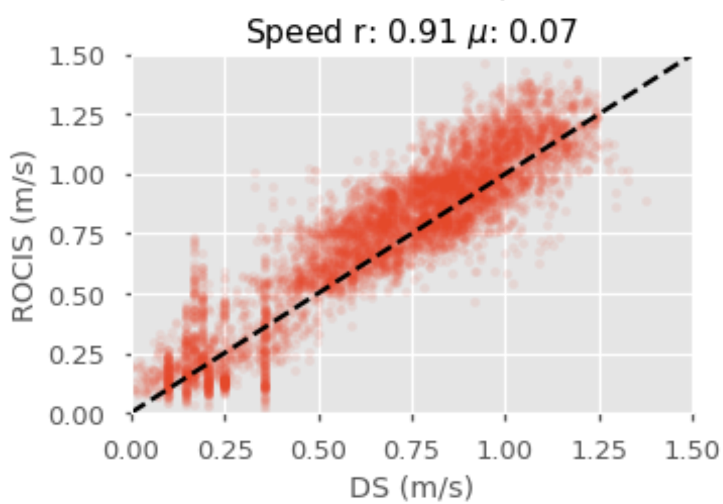
DopplerScatt GoM Eddy Validation

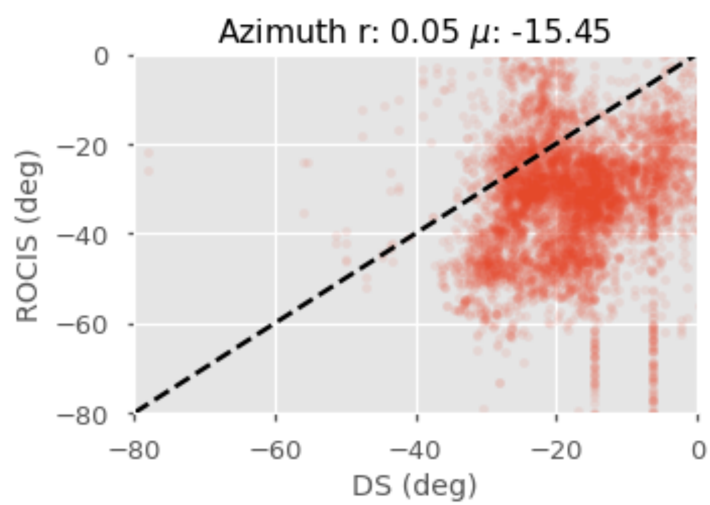
DopplerScatt Speed Data Overlaid with ROCIS Speed Data



In March 2018, DopplerScatt flew over a large Gulf of Mexico Eddy south of New Orleans.

Ocean surface current data were collected at the same time with Fugro's Remote Ocean Current Imaging System (ROCIS) which uses FFT's of space-time ocean wave imagery and the dispersion relation to solve for surface currents.

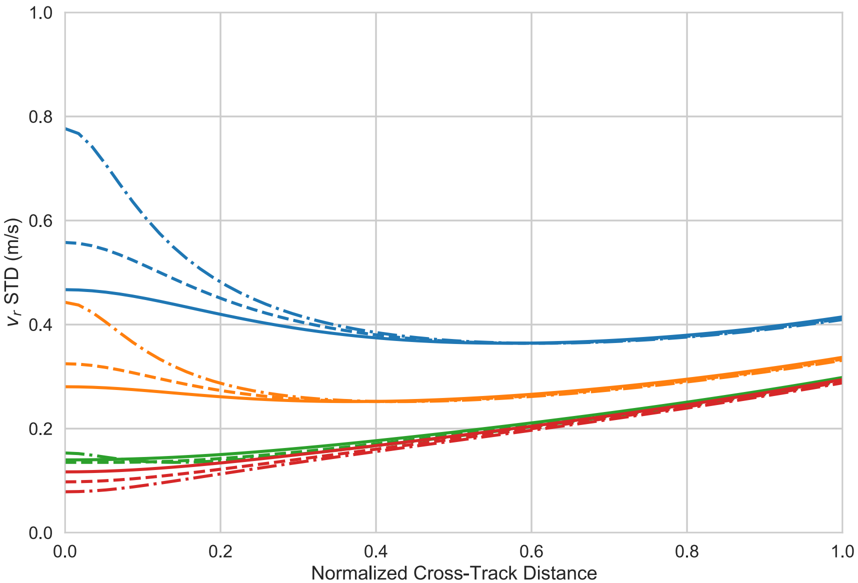


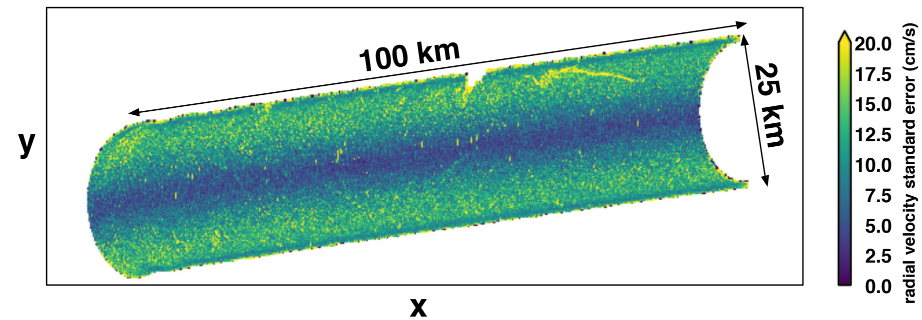


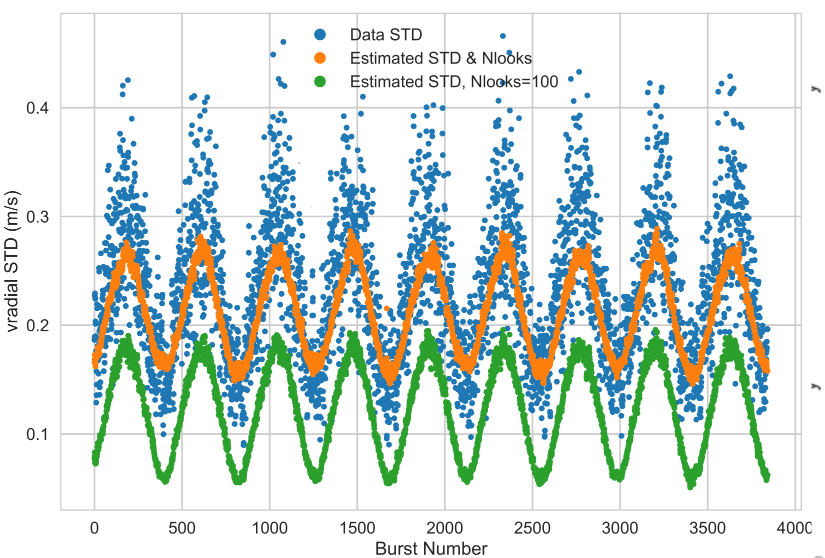
Preliminary results. Analysis on both sides still ongoing.

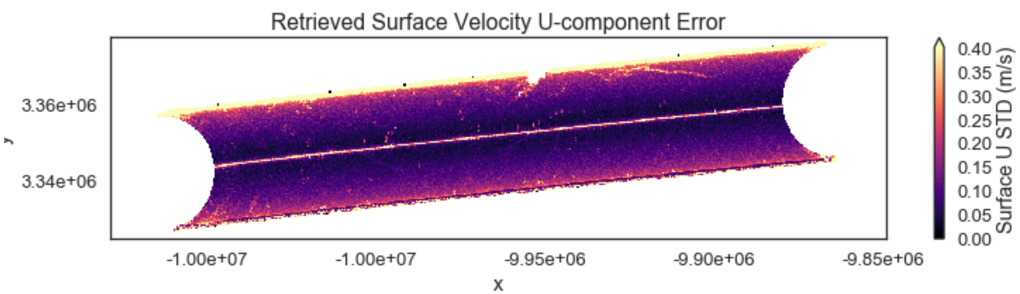
ROCIS data courtesy of Chevron and Fugro.

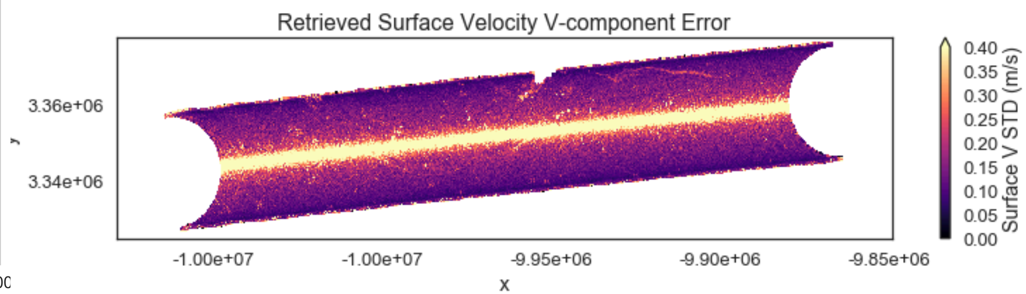
Surface Velocity Random Errors





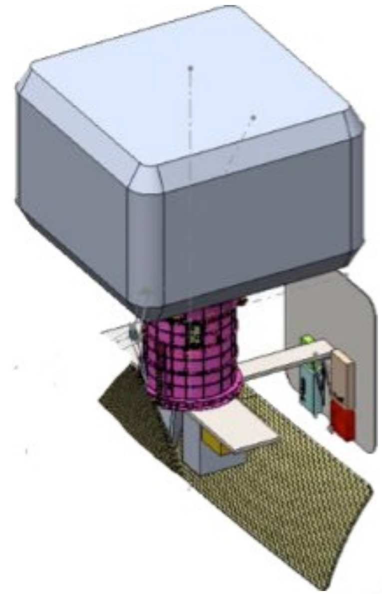


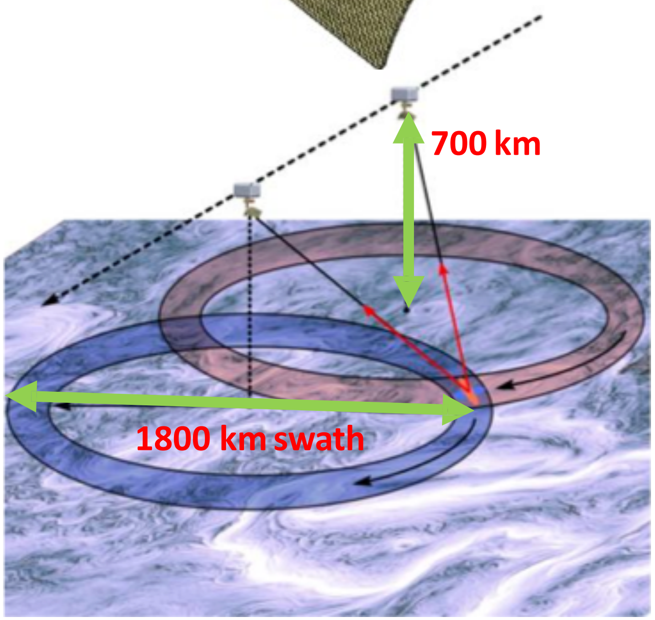




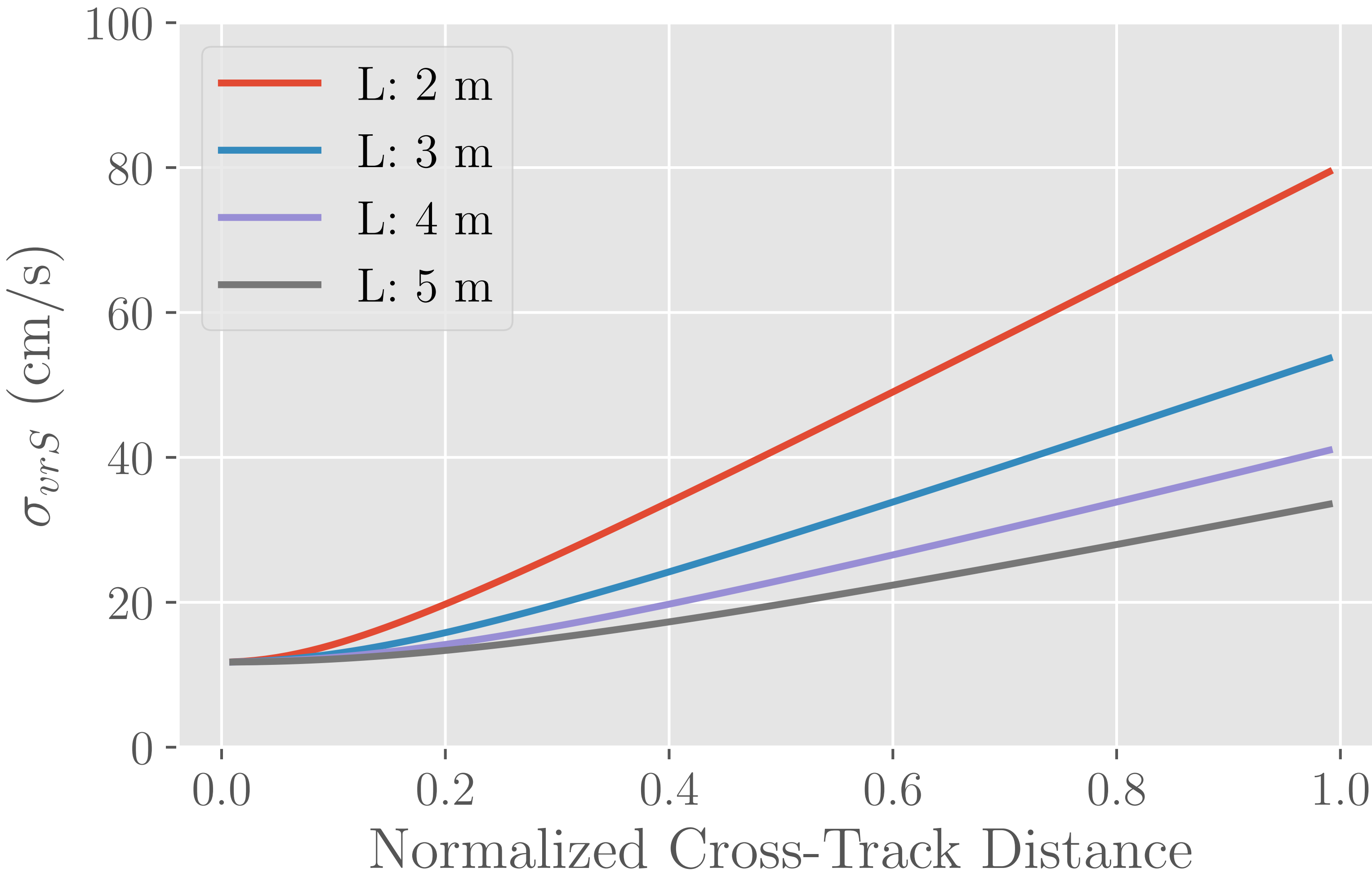
Winds and Currents Mission Concept

- Studies have been conducted jfor a potential winds and currents mission.
- The mission was found feasible with existing technology and of moderate cost.
- Spaceborne performance:
  - Wind resolution <5km allowing coastal coverage.
  - Current resolution O(30km) @ O(10 cm/s) precision
  - Both measurements roughly on 2 times/day.

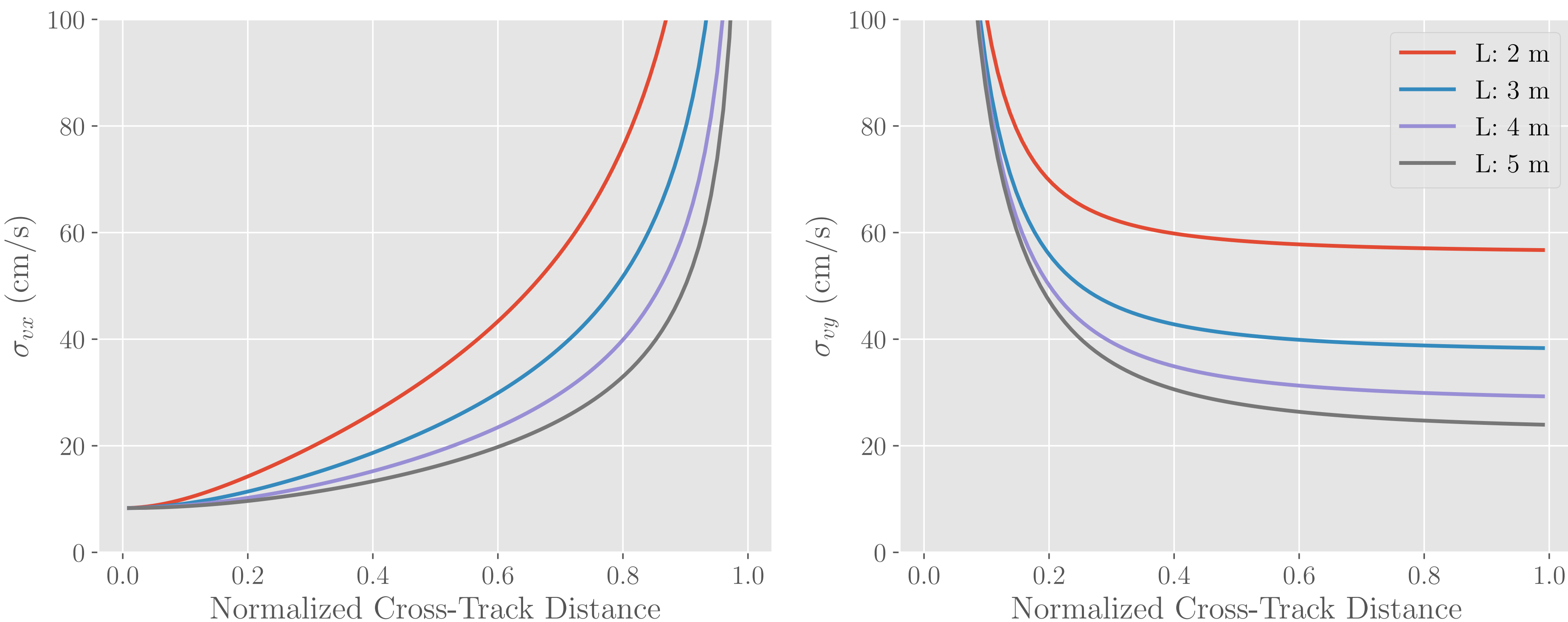




Radial Velocity Performance
5 km resolution



Velocity Component Performance
5 km resolution



Random errors would decrease by a factor of 5 for 25 km resolution

Multi-temporal averaging further reduces random error